Juno at Jupiter: The Mission and Its Path to Unveiling Secrets of the History of the Solar System

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***Abstract* — The Juno mission is described, focusing on its orbits at Jupiter, how the plan evolved, and science return so far.**

Juno is a NASA New Frontiers spacecraft in a near-polar highly elliptical 53-day orbit at Jupiter. Since arrival in July 2016, it has used 9 science investigations to study the planet's atmospheric composition and structure, magnetic and gravity fields, and polar and extended magnetosphere. A radiation monitoring investigation contributes to our understanding of Jupiter's environment. Juno's primary science goal is to understand the origin and evolution of Jupiter, to shed light on how the Earth and other planets formed. Baseline objectives will be satisfied with 32 science orbits, a spin-stabilized solar powered spacecraft, an electronics vault for radiation shielding, and a robust payload with microwave receivers, X- and Ka-band radio science hardware, vector magnetometers, high- and low-energy charged particle detectors, radio and plasma wave antennas, UV and IR spectroscopic imagers, and a visible light camera for public outreach. Observations are made in a limited number of orientations, including Gravity Science (spin axis and main antenna pointing to Earth), and microwave atmospheric sounding (spin plane passing through Jupiter's center). Prime science data are collected near closest approach (perijove), plus calibrations, occasional remote sensing, and continued magnetospheric observations in the outer parts of the orbit.

Juno's mission plan has evolved since the 2005 proposal due to design and ops choices, e.g., mission design (cruise or early orbital trajectory), orbit period (11, 14, then 53 days), perijove attitudes (2 or more), and DSN coverage (34- and 70-m stations). Choices were partly motivated by the effect on science return.

Selected preliminary science results are summarized, including the benefits of decisions as the plan evolved. Juno has begun to unveil Jupiter – peeling apart its interior by measuring gravity and magnetic fields, using microwaves to probe its atmosphere down to 100s of km, exploring its polar and extended magnetosphere, and imaging the poles for the first time. In doing so, it is revealing secrets of the history of the Earth and solar system.

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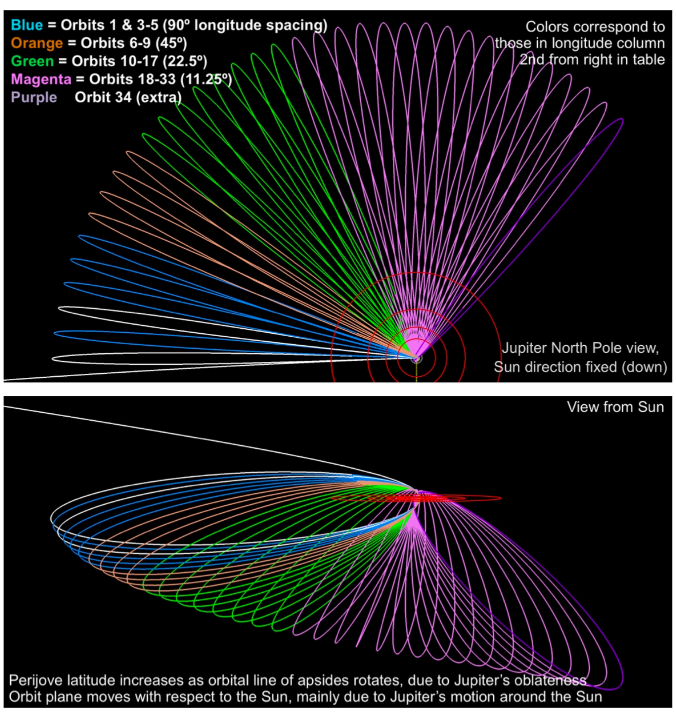


Perijove (data to right are specified at perijove, except last 2 columns)			Sun Range	Earth Range	Inc	Oblate Altitude	Lat	Off-Sun Angle	SEP	Sys III W Long at EqX	Local Time at AJ
#	Type	Date (UTC)	(AU)	(AU)	(°)	(km)	(°)	(°)	(°)	(°)	(hrs)
0	JOI	Jul 5, 2016	5.44	5.81	89.8	4494	2.7	91.8	64.1	33.3	6.0
1	GRAV	Aug 27, 2016	5.45	6.37	89.9	4163	3.8	4.1	22.6	96.6	5.7
2	Post-SM	Oct 19, 2016	5.45	6.39	90.0	4179	4.7	3.3	18.2	348.8	5.5
3	GRAV	Dec 11, 2016	5.46	5.85	90.2	4153	5.6	9.1	61.6	6.8	5.2
4	MWR	Feb 2, 2017	5.46	5.03	90.6	4304	6.6	14.2	110.8	276.5	4.9
5	MWR Tilt	Mar 27, 2017	5.46	4.48	91.0	3404	7.6	25.0	167.1	186.8	4.7
6	GRAV	May 19, 2017	5.45	4.69	91.6	3497	8.5	7.5	135.4	142.0	4.4
7	MWR	Jul 11, 2017	5.45	5.43	92.2	3500	9.5	26.4	85.7	51.9	4.2
8	GRAV	Sep 1, 2017	5.45	6.15	92.9	3500	10.4	7.2	42.5	321.9	3.9
9	MWR Tilt	Oct 24, 2017	5.44	6.44	93.6	4035	11.3	35.0	1.9	232.0	3.6
10	GRAV	Dec 16, 2017	5.43	6.14	94.4	4322	12.2	6.8	40.8	299.5	3.4
11	GRAV	Feb 7, 2018	5.43	5.39	95.3	3500	13.1	10.5	86.9	209.5	3.1
12	GRAV	Apr 1, 2018	5.42	4.62	96.1	3500	14.0	6.9	139.2	119.5	2.9
13	GRAV	May 24, 2018	5.41	4.43	97.0	3500	14.9	3.1	163.4	29.5	2.6
14	GRAV	Jul 16, 2018	5.39	4.97	97.7	3500	15.7	10.2	109.7	74.5	2.4
15	GRAV	Sep 7, 2018	5.38	5.75	98.4	3500	16.6	9.7	63.6	344.5	2.1
16	GRAV	Oct 29, 2018	5.37	6.28	99.1	3500	17.4	3.9	21.5	254.5	1.9
17	GRAV	Dec 21, 2018	5.35	6.26	99.7	5054	18.1	3.6	20.2	164.5	1.7
18	MWR XTk	Feb 12, 2019	5.34	5.70	100.2	3500	18.9	92.9	64.0	198.2	1.4
19	GRAV	Apr 6, 2019	5.32	4.86	100.6	5306	19.6	10.0	112.1	108.3	1.2
20	GRAV	May 29, 2019	5.30	4.31	101.0	7247	20.3	2.5	166.7	18.2	0.9
21	GRAV	Jul 21, 2019	5.29	4.50	101.2	7975	21.0	7.5	137.1	288.2	0.7
22	GRAV	Sep 12, 2019	5.27	5.22	101.2	7975	21.6	11.0	86.9	333.2	0.4
23	GRAV	Nov 3, 2019	5.25	5.93	105.5	3500	22.4	7.4	42.7	243.3	0.2
24	GRAV	Dec 26, 2019	5.23	6.21	105.4	5041	22.9	0.2	0.8	63.3	23.9
25	GRAV	Feb 17, 2020	5.21	5.91	105.2	6728	23.4	7.2	41.3	153.2	23.7
26	GRAV	Apr 10, 2020	5.19	5.17	105.1	3500	24.0	11.1	85.7	85.8	23.4
27	GRAV	Jun 2, 2020	5.17	4.40	104.7	3500	24.6	7.9	135.7	355.8	23.2
28	GRAV	Jul 25, 2020	5.15	4.15	104.2	3500	25.3	2.3	168.2	265.7	22.9
29	GRAV	Sep 16, 2020	5.13	4.64	103.7	3500	25.9	10.3	113.7	175.7	22.6
30	GRAV	Nov 8, 2020	5.11	5.44	103.1	3500	26.6	10.2	66.0	220.8	22.4
31	GRAV	Dec 30, 2020	5.10	5.99	102.4	3500	27.3	4.3	22.9	130.7	22.1
32	GRAV	Feb 21, 2021	5.08	6.01	101.5	4889	28.0	3.5	18.4	40.7	21.8
33	GRAV	Apr 15, 2021	5.06	5.49	100.6	3500	28.8	9.9	59.9	310.8	21.6
34	Extra	Jun 7, 2021	5.05	4.69	99.7	3500	29.6	11.2	105.0	220.7	21.3
35	Deorbit	Jul 30, 2021	5.03	4.08	98.8	-700	30.5	4.4	157.4		

Figure 1. Juno Orbital Trajectory (colors in left columns correspond to orbit type, altitude is jovi-detic, latitude is -centric)

1. INTRODUCTION

Previous Work

Earlier overview papers on the Juno mission for the IEEE conference or similar meetings have provided a status at the time of the project's preliminary design phase [1-2], in the year prior to launch [3], during early cruise [4], 2 years after launch at the time of Earth Flyby [5], and less than 2 years from arriving at Jupiter [6]. A series of papers in *Space Science Reviews* describes the science instruments and planned mission and science at Jupiter in greater detail [7].

Organization of Paper

This paper first gives an overview of the Juno mission plan, focusing on its orbits at Jupiter. The main part of the paper focuses on the evolution of the plan since pre-launch, during cruise, and in early orbit operations. The choices made and lessons learned are highlighted, in particular how they relate to science results. Preliminary science results are described.

2. BACKGROUND AND SCIENCE OBJECTIVES

From Proposal to Mission

Juno is named for the Roman goddess, Jupiter's sister and wife. After a competitive 2-step proposal process, Juno was selected in May 2005 as the second mission in NASA's New Frontiers program. Originally scheduled to launch in 2009, due to programmatic budgetary constraints, it was slipped to 2010 immediately after selection, and again in early 2006 to a 2011 launch. The resulting extended Phase B let the project take advantage of extra time for requirements development, maturing the early design, and risk reduction [2]. A successful Preliminary Design Review in 2008 and Critical Design Review in 2009 preceded the Assembly, Test, and Launch Operations campaign that led to launch on 8/5/11.

Science Objectives

Juno's science objectives encompass four scientific themes: origin, interior structure, atmospheric composition and dynamics, and polar magnetosphere. The mission's goal is to improve our understanding of the solar system by helping to reveal the origin, evolution, and structure of Jupiter.

Juno addresses objectives central to three science divisions at NASA: Planetary Science, Heliophysics, and Astrophysics. Jupiter can reveal conditions in the early solar system and ultimately provide insight into the formation and evolution of our planetary system. The abundance of heavy elements in Jupiter's atmosphere and the mass of a solid core will discriminate among models for giant planet formation. Juno will constrain the mass of Jupiter's core by mapping its gravity field, and will use microwave atmospheric sounding to provide global abundances of oxygen (in water) and nitrogen (in ammonia). The history of Jupiter will be revealed by mapping the gravity and magnetic fields with sufficient resolution to constrain Jupiter's interior structure, the source region of the magnetic field, and the nature of deep convection. Sounding deep into the atmosphere will determine to what depth the belts and zones penetrate. Juno performs the first survey and exploration of the three-dimensional structure of Jupiter's polar magnetosphere. Table 1 shows the high-level goal and questions that Juno expects to address, along with more specific science objectives.

Table 1. Juno Goal, Questions, and Science Objectives

Mission goal
• Juno will improve our understanding of solar system history by investigating the origin and evolution of Jupiter
• To accomplish this goal, the mission will study Jupiter's origin, interior, atmosphere, and magnetosphere
• This will tell us how giant planets form and evolve, helping us understand how other planetary systems evolve
Questions about Jupiter that Juno expects to address
• How did Jupiter form?
• How is the planet arranged on the inside?
• Is there a solid core, and if so, how large is it?
• How is its vast magnetic field generated?
• How are atmospheric features related to the movement of the deep interior?
• What are the physical processes that power the auroras?
• What do the poles look like?
Questions about giant planets and other solar systems
• When in the early solar system did the gas giants form?
• How did the birth of Jupiter and its gas-giant sibling, Saturn, differ from the ice giants Uranus and Neptune?
• What is the history of water and other volatile components across our solar system?
• How do processes that shape the present character of planetary bodies operate and interact?
• What does our solar system tell us about the development and evolution of other planetary systems, and vice versa?
Science objectives
• Origin – Constrain the abundance of water and place an upper limit on the mass of Jupiter's dense core to distinguish among theories of the planet's origin
• Interior – Investigate Jupiter's interior structure and how material moves deep within the planet by mapping its gravitational and magnetic fields
• Atmosphere – Map variations in atmospheric composition, temperature, cloud opacity, and dynamics to depths greater than 100 bars at all latitudes
• Magnetosphere – Characterize and explore the three-dimensional structure of Jupiter's polar magnetosphere and auroras

Mission and Operations Implementation

Juno's objective was to put a spacecraft with a unique payload into a polar orbit at Jupiter to perform multiple orbits. Remote sensing, in-situ, and Gravity Science measurements characterize Jupiter's interior, atmosphere, and polar magnetosphere. Juno mainly studies Jupiter's present state, but examining time variable phenomena such as secular variability in the magnetic field, external influences on the gravity field, and polar magnetospheric aurora sheds additional light on the structure of the Jovian interior and polar magnetosphere. The investigation is enabled by observations of the polar region and from very close perijove vantage points. A solar powered spin-stabilized spacecraft with an electronics vault for radiation shielding carries X- and Ka-band radio science hardware, microwave receivers, vector magnetometers, high- and low-energy particle detectors, radio and plasma wave antennas, UV and IR spectroscopic imagers, and a visible light public outreach camera. A radiation monitoring investigation also contributes to our understanding of Jupiter's environment using data from the star cameras and some of the science instruments. Observations are made by orienting the spin axis and with repetitive operations, without using a scan platform or instrument pointing. Gravity Science requires communicating with DSN stations (Earth-pointed spin axis), whereas microwave atmospheric sounding requires nadir pointing (orienting the spin plane through the center of Jupiter). The 2 main spacecraft spin axis orientations (Gravity Science = GRAV, and Microwave Radiometer = MWR) support most science measurements. Other instruments use both orbit orientations. The primary science measurements are made within 3 hours of perijove, but calibrations, magnetospheric science observations, and occasional remote sensing are planned throughout the orbits.

Juno mission operations are distributed among the Jet Propulsion Laboratory (JPL) in Pasadena, California, Lockheed Martin Space Systems Company (LM) in Denver, Colorado, the Juno Science Operations Center (JSOC) at Southwest Research Institute (SwRI) in San Antonio, Texas, and instrument teams across the U.S., plus JIRAM in Italy and ASC in Denmark. The idea behind distributed ops is to let scientists and instrument experts operate payloads from home institutions as efficiently as possible and with minimal interaction.

Since activities and geometry during science orbits are highly repetitive, operations are based on two orbit types. Activity profiles in MWR and GRAV orbits are very similar, and it was clear early on that adjacent orbits will be much more similar than early and late orbits, so sequences can be developed efficiently with very small adjustments from orbit to orbit. Making incremental changes along the way in orbital ops has turned out to work well. This strategy gives flexibility and benefits from cost savings and reduced risk associated with multi-mission uplink processing tools. Science Activity Plans (SAPs), detailed instrument data collection plans at the activity level, are the starting points for a 2-pass sequencing process prior to sequence uplink. Every orbit consists of 2 sequences, the first starting a day before perijove, and the second a day before apojove.

Spacecraft and Instruments

Juno's team of scientists and engineers designed the flight system to accomplish its scientific objectives as efficiently as possible. The LM-built and integrated spacecraft (Figure 2) [5] is spin-stabilized, with 12 monopropellant thrusters for turns, nutation damping, spin control, and ΔV. Telecom uses X-band hardware with high-, medium-, and 2 low-gain antennas (HGA, MGA, LGAs), and a toroidal LGA viewing the spin plane, e.g., for main engine burns. Gravity Science Ka-band hardware uses the 2.5-meter HGA. Electric power comes from 3 large solar arrays, making Juno the spacecraft that has operated farthest from the Sun (5.46 AU) with solar power. Redundant Command and Data Handling (C&DH) units use flight software (FSW) executing on RAD750 processors; they have file system memory for data that can persist after a reboot or side swap, and 25 Gbits of science data storage. Large burns were done on a Leros-1B bipropellant main engine. A titanium vault protects sensitive electronics from the Jupiter radiation environment, and is shielded thermally by the HGA. Juno's mass at launch was 3625 kg with propellant. It is 20 meters in diameter with its solar arrays, and 4.5 meters in height. All instruments except MAG and GRAV are accommodated on the core spacecraft bus.

The Juno payload consists of 9 investigations, shown in Figure 2. FGM and ASC make up the MAG investigation that will map Jupiter's magnetic field. MWR and JIRAM will characterize the atmosphere. GRAV will map the gravity field. Waves, UVS, JEDI, and JADE will characterize the polar magnetosphere. JunoCam is designed for education and public outreach. The attitude in MWR orbits, with the spin plane through Jupiter, is optimized for MWR, JIRAM, and JunoCam, but they can also operate in GRAV orbits. Gravity Science requires Earth-pointing in GRAV orbits to use Ka- and X-band over the HGA, but also uses X-band and the MGA or an LGA in MWR orbits. MAG, Waves, UVS, JEDI, and JADE operate in all orbits. Onboard the spacecraft, instruments use spin phase information provided by the spacecraft and magnetic field vectors provided by MAG. Other data are correlated on the ground, using reconstructed timing and pointing.

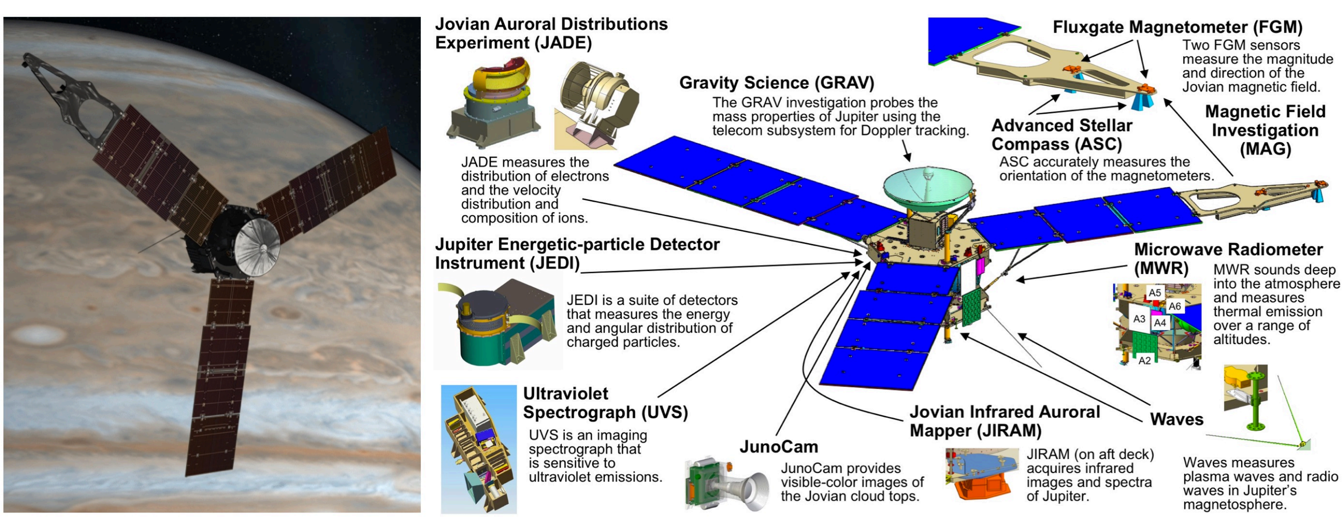


Figure 2. Spacecraft and Instruments

Trajectory and Navigation

Juno reached Jupiter using a ΔV-EGA trajectory (Figure 3), with large Deep Space Maneuvers (DSMs) (ΔV or delta velocity part of the name), and an Earth Flyby (EFB) (EGA or Earth gravity assist). Total cruise time = 4 years 11 months.

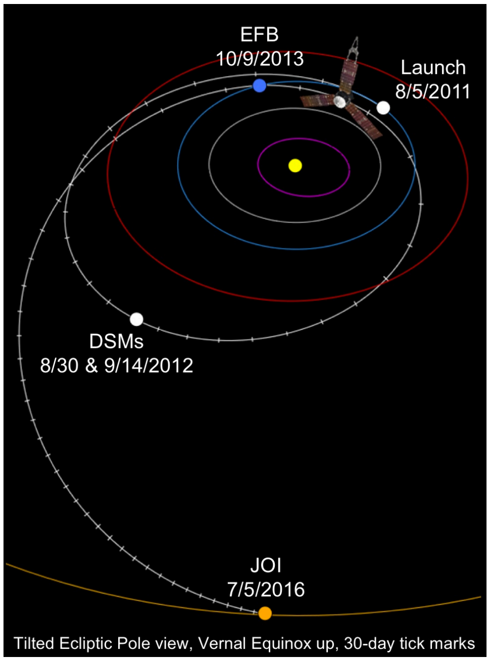


Figure 3. Interplanetary Trajectory

Jupiter Orbit Insertion (JOI) on 7/5/16 UTC (or 7/4/16 in the U.S.) was timed so that 2 capture orbit periods resulted in a 10/19/16 date for the Period Reduction Maneuver (PRM), 2 perijoves (PJs) later. The idea of capture orbits was originally implemented to save ΔV (compared to direct insertion into shorter period orbits), due to (a) minimizing DSM ΔV by arriving at Jupiter earlier, and (b) lower gravity losses. PRM would have put Juno into a 14-day orbit, but was canceled due to concerns about the reliable operation of check valves in the propulsion subsystem, and it was decided to remain in 53-day orbits.

Although called a 53-day orbit, it is really 53 days x 0.9975 = 52.867 days on average. The difference arises from correlating Earth's rotational period and Jupiter's synodic period with respect to the Earth, where the latter is ~399 days, the time between solar conjunctions (0.9975 = 1 – 1/399) [8]. This keeps perijoves over DSS-25 at Goldstone, the DSN's only station capable of Ka-band uplink. Orbit trim maneuvers (OTMs) after perijove are used to target the timing of the next close pass so that longitudes of post-perijove equator crossings are evenly spaced, 11.25° apart, after 32 orbits. A 4-8-16-32 grid is built (Figures 1 and 8), with longitudes 90° apart after 4 orbits, 45° apart after 8 orbits, and 22.5° apart after 16 orbits, making the magnetic field investigation more robust in the event of missed PJ longitudes or an early mission termination. Jupiter's oblateness causes the line of apsides to rotate nearly 1° per orbit, so that PJ latitude ranges from 3°N at JOI to 31°N at PJ35. The inbound equator crossings initially occur outside of Callisto's orbit (Figure 1), but later in the mission they get closer to Jupiter.

A full set of 32 orbits is followed by one extra or spare orbit (margin in the event of a missed perijove longitude), and then a deorbit maneuver near apojove of the final orbit to comply with planetary protection for the Galilean moons.

With JOI counting as perijove 0 (PJ0), the first orbit with a longitude useful for the magnetic field investigation was PJ1. No science (except X-band tracking for GRAV) was achieved at PJ2 due to the PRM cancellation and subsequent pre-PJ2 safe mode. PJ3 through PJ33, if all are successful, will finish the 32 baseline science orbits. PJ34 is a spare PJ. PJ35 on 7/30/21 marks the planned End of Mission (EOM) with an impact into Jupiter following the deorbit maneuver.

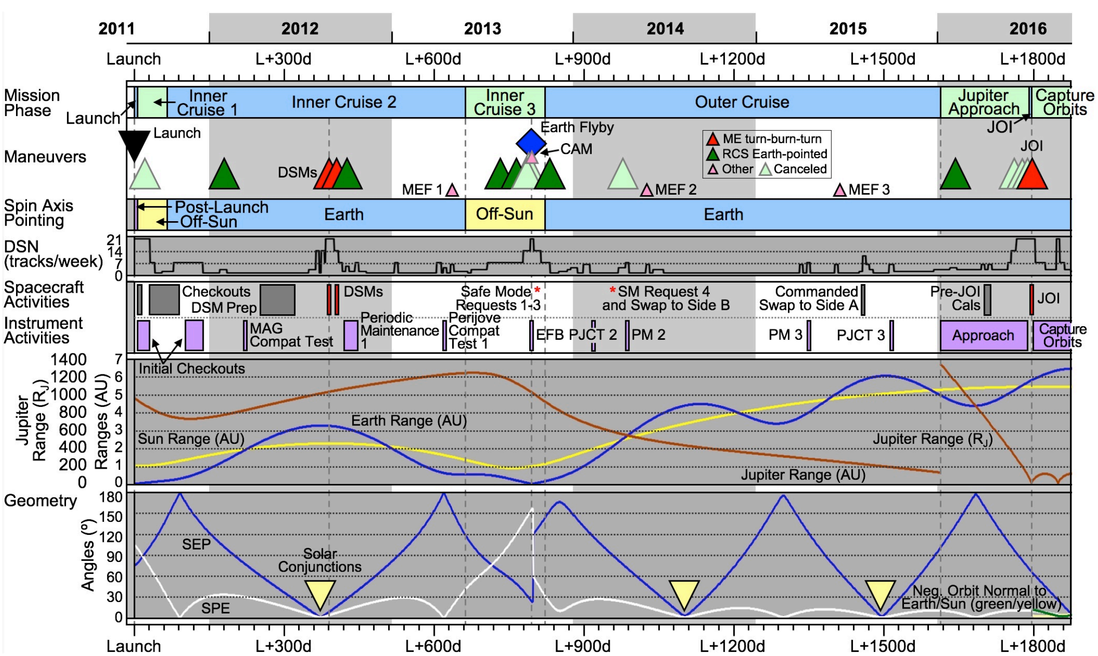


Figure 4. Cruise Timeline

3. JUNO MISSION PLAN

Overview of Mission Phases

A Juno cruise timeline is shown in Figure 4, and cruise and orbital trajectories in Figures 3 and 1. After a brief Launch phase, interplanetary cruise was divided into 3 Inner Cruise phases (corresponding to when the spin-axis and HGA had to be pointed at or near the Sun for thermal or telecom reasons, vs. when it could be Earth-pointed) as well as phases for Outer Cruise and Jupiter Approach prior to JOI. After JOI, there are 2 orbital phases, Science Orbits and Deorbit (before the project's decision to cancel PRM and remain in 53-day orbits, there were phases for early orbits and PRM).

Cruise [4-6]

Early cruise spacecraft activities included checkouts, cals, the first TCM, DSM preparation, and spin rate adjustments.

DSMs served to minimize first-time events during JOI and characterize main engine performance. The DSMs, like JOI and PRM, were large maneuvers (732 m/s together) and required the HGA to be pointed ~90° away from Earth. Subcarrier tones from the toroidal LGA enabled monitoring of events during each of these 4 planned main engine burns.

Early payload activities included initial checkouts for all the instruments, high-voltage checkouts for JADE, JEDI, and UVS in Inner Cruise 2, antenna and detector door deployments, calibrations, FSW updates, and periodic instrument maintenance. Multi-instrument compatibility tests, to validate simultaneous instrument operations and the magnetic and electromagnetic compatibility of the payload, were performed in 4 rounds from 2012 through 2015.

The Inner Cruise 3 phase, including EFB, was characterized by pointing the spin axis near the Sun to thermally manage vault electronics around perihelion (0.88 AU). The MGA and LGAs were used at low data rates, and most instruments were off for the 4 months before EFB. Two TCMs corrected EFB targeting, and one after EFB cleaned up errors and corrected JOI targeting.

Earth Flyby occurred at 559 km altitude ~26 months after launch. Instruments collected calibration data at the only planet and magnetosphere on the way to Jupiter, and the ops team and end-to-end data flow were exercised. Juno's only solar eclipse (19 minutes) after the launch phase was during EFB. Instruments were on during cruise, although at a level of activity lower than planned for science orbit operations.

As the only opportunity to sense a planet and its magnetic field up close in cruise, and as a chance to exercise the ops team, Earth Flyby was planned and conducted as a test of science ops, subject to flight system constraints, e.g., thermal. To focus on simulating perijove while benefiting from the Earth and Moon encounters, several instruments came on 3-4 days before EFB closest approach (C/A), avoiding a data backlog period in the months before EFB, and several stayed on after C/A. Significant differences from a Jupiter perijove included the less severe environment, larger telecom margins, more DSN coverage than in orbit, no pre-EFB turn like the one ~1 day before perijove, and other geometry details. Juno stayed very close to Sun-pointed at C/A. The off-Earth and -Moon angles were close to 90° very briefly near C/A, for Earth and Moon spin plane viewing opportunities by remote sensing instruments. Approaching C/A, the ASC cameras supporting the MAG investigation viewed the Moon passing in front of the Earth, then kept imaging the Earth as it grew larger in the field of view. These images, plus JunoCam Earth images and Waves detection of ham radio signals near C/A, acted as high value public engagement opportunities [9] not otherwise available until Jupiter.

All instruments except JADE, MWR, and Ka-band Gravity Science collected data at EFB. JunoCam, JIRAM, and UVS observed the Moon when visible near the spin plane or at its closest approach. JunoCam and UVS also viewed the Earth near EFB C/A. All fields and particles instruments except JADE were used during the C/A period. Waves did noise cancellation tests, important for orbital preparation. GRAV took X-band Doppler data near C/A to investigate apparent tracking anomalies during previous spacecraft flybys. The SRU was used to practice for orbital radiation monitoring, coordinating with instruments involved in that investigation.

After EFB, Juno had its first 3 safe mode requests [6]. The first was shortly after closest approach, as the battery voltages fell below fault protection low state-of-charge limits during eclipse. Two days after recovery and safe mode exit, a second safe mode request occurred when the Stellar Reference Unit's (SRU) Thermal Electric Cooler current exceeded its limits and the SRU was marked failed. The third safe mode request, in the day after the second and before recovery was done, took place when a Sun-Earth tagup timer expired (this timer ensures Sun-point in safe mode).

Juno entered safe mode a fourth time on 3/19/14 [6] when it experienced a warm reset, and during the reboot had a second warm reset that resulted in a side swap from side A of C&DH to side B. Following recovery and a careful investigation, the project decided to go back to side A for operational evaluation in August 2015.

Juno cruise instrument activities evolved towards relying on strategic vs. real-time commanding, less ground interaction needed to respond to downlinks, and mitigation of anomalies, all consistent with continued preparation for orbital ops.

Post-EFB activities included routine observations managed via the cruise sequencing and instrument activity planning processes, subject to basic spacecraft constraints, although requests with more resource impacts were also considered.

Jupiter Orbit Insertion (JOI)

An early pre-JOI activity was to ensure the battery was fully charged. All instruments were turned off by JOI-5d and remained off for JOI itself. The JOI phase lasted from JOI-4d to JOI+1h, and included the JOI critical sequence. JOI, the second critical event of the mission (after launch), was centered on PJ0, and slowed Juno sufficiently to be captured by Jupiter (Figure 5). A cleanup maneuver at JOI+15.6d was used to ensure the timing of the large PRM burn planned 2 PJs later. DSN coverage was continuous from prior to JOI until the cleanup burn, after which a mix of 34- and 70-m's was used in the capture orbits. Orbit insertion was required for mission success; fault protection software maximized the probability of the critical sequence finishing, and normal safe mode was disabled. The JOI burn used the main engine, with a ΔV of 542 m/s, lasted 35 minutes, and was viewable from Earth (using the toroidal LGA since the spin axis was ~90° off-Earth). Tones sent burn progress information to Goldstone and Canberra 70-m antennas. A constant thrust vector was used for the burn. The total time off-Sun, including turns, was less than 2 hours. JOI and PRM were timed with a perijove longitude near minimum magnetic field strength, allowing a spin-up to 5 RPM and reducing risks associated with spin-induced magnetic field effects in hardware. As planned, the JOI burn fell between the radiation peaks from magnetospheric ions and electrons which were on each side of perijove. Perijove was at 1.06 Rj range (4500 km altitude) and 3°N latitude. After Juno was safely in a polar orbit, its spin axis was realigned with the HGA.

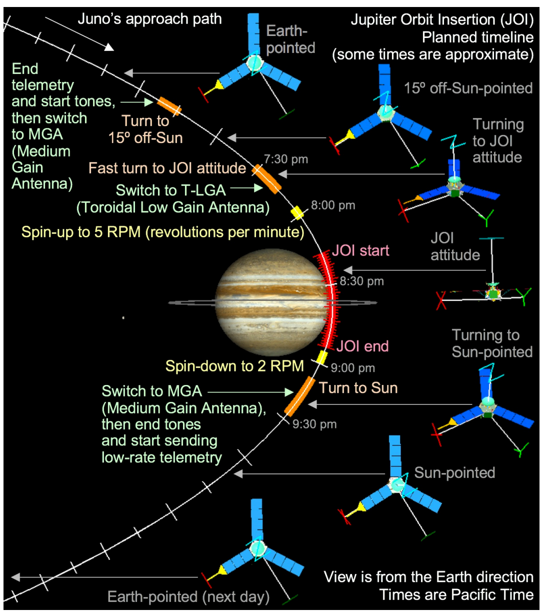


Figure 5. Jupiter Orbit Insertion (JOI) Timeline

Science Orbits Overview

Operations Philosophy — Juno continues to refine its strategy for repetitive ops at Jupiter. Orbital sequences include OTMs and other maneuvers, and required uplinks, as well as DSN passes using DSS-25 at perijove and a mix of 34-m's and 70-m's after perijove and elsewhere in the orbit.

The ability to incorporate experience from one PJ into the next is enabled by a mission with 53-day orbits, given that strategic development for the next PJ only starts on the heels of the prior PJ (rather than significantly overlapping in the case of the 11- or 14-day orbits that were planned earlier). Orbit-to-orbit variations are mainly due to timing and data rate changes, or unique remote sensing observations. Differences between MWR and GRAV orbits are focused near perijove: (a) GRAV replaces a pre-PJ turn to MWR attitude with one to GRAV attitude, (b) GRAV has a DSS-25 HGA pass at PJ instead of an MGA pass for MWR, and (c) post-PJ OTM timing and setup is slightly different.

Terminology — The Science Orbits phase begins at the end of the JOI phase after perijove 0 (PJ0), and continues to the start of the Deorbit phase just before apojove 34 (AJ34-1h).

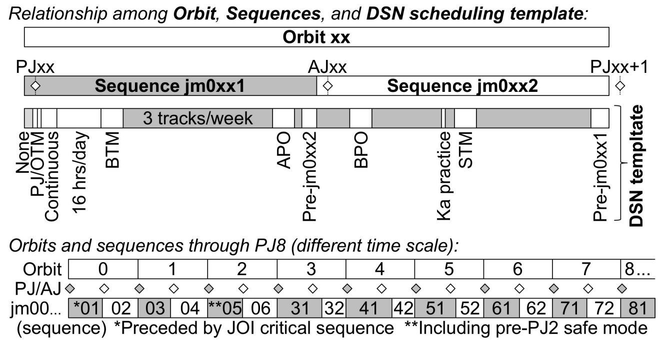


Figure 6. Science Orbits Terminology

Figure 6 shows how orbits, sequences, and the DSN scheduling template are related. Navigation (Nav) orbits are defined from apojove AJxx-1 through AJxx, including PJxx. However, for science and ops, "Orbits" are considered to run from PJ-1d (truncated to the even hour) to the next PJ-1d, with Orbit xx including PJxx near the start.

The mission uses Orbit 1 plus Orbits 3 through 33 to obtain 32 perijoves to meet MAG and other science requirements. Orbit 34 is bookkept as an extra science orbit. OTMs are typically small (less than ~5 m/s) and planned after perijove science observations, at PJ+7.5h in Orbits 3 through 33, to target the equator crossing longitude needed for MAG observations in the next orbit. Other maneuvers are required near apojove or inbound to the following perijove. There is no need for an OTM after PJ34. The deorbit maneuver (19 m/s) is planned near AJ34.

There are 2 sequences in each orbit. Starting with Orbit 7, sequences run from PJ-1d to the next AJ-1d, or from AJ-1d to PJ-1d. Each sequence is defined by the number of the PJ in it or in the previous sequence, and the PJ type (MWR or GRAV). E.g., the jm0071 (or jm0071m) sequence was the first ~26.5-day sequence, an MWR type, from PJ7-1d to AJ7-1d. In orbit 6 and earlier, as the project adjusted to remaining in 53-day orbits, the first sequence (with PJ) was usually longer than the second and ended after AJ. Since they occurred before the project adapted to 53-day science orbits, Orbits 0-2 used different sequence numbering.

Geometry — For a 5-year Jupiter mission, with 36 perijoves in 53-day orbits, minimum and maximum Earth ranges (at opposition and solar conjunction) each occur roughly every 13 months (every ~7.5 orbits [10], so that a conjunction near PJ9 repeats near PJ24, and one near AJ16 repeats near AJ31 – e.g., see Figure 17). Sun range was maximum at 5.46 AU in early 2017 (Jupiter aphelion); minimum will be 5.03 AU at EOM in mid-2021 (Figure 7, and table in Figure 1).

Juno was conceived as a polar orbiter with inclination near 90°, but to avoid an eclipse after PJ22 in 53-day orbits, the inclination will be allowed to grow as large as 105.5° (with a concurrent small change in the orbit's ascending node). The resulting progression of orbits is shown in the top part of Figure 1, where the view is from the Jupiter north pole and the Sun direction is fixed straight down. The rotation about the Sun direction is mainly due to Jupiter's orbit about the Sun; Juno's orbit is otherwise nearly inertially fixed in space, aside from variations in inclination and node. The 4-8-16-32 buildup of magnetic field longitudes at PJ is shown in Figure 8 (and see section 2).

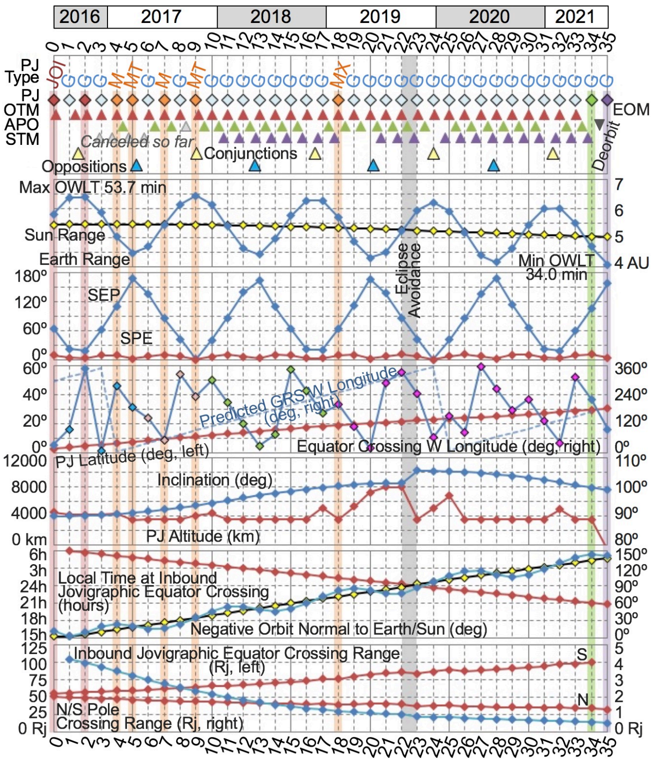


Figure 7. Orbital Geometry vs. Perijove

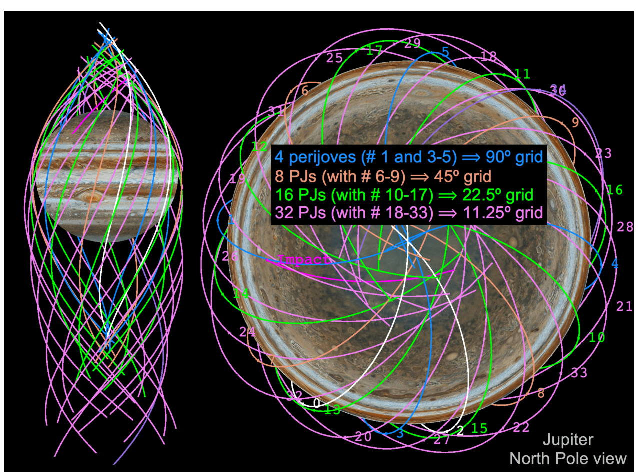
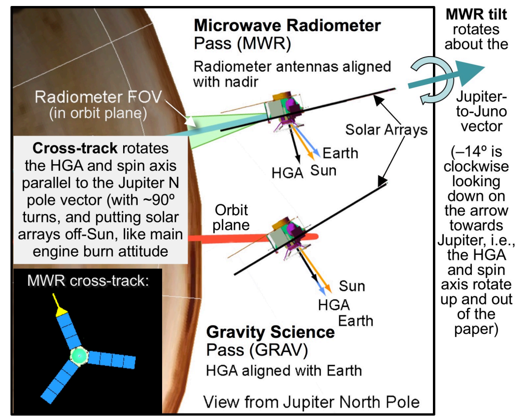


Figure 8. Global Coverage from a Net of Perijove Passes

Gravity Science requires communicating with DSN stations (Earth-pointed spin axis), whereas microwave atmospheric sounding requires nadir pointing (orienting the spin plane through the center of Jupiter) (Figure 9). MWR attitudes are used in early orbits when the spin-axis to Sun angles are not too large and the solar arrays can supply sufficient power. Earth-pointed GRAV attitudes are used in most of the other orbits, so that two-way X- and Ka-band links between the DSN and the HGA are maintained for the PJ pass. During later orbits, MWR attitudes and others with a large off-Sun angle for the solar arrays can only be maintained for very limited durations near perijove. Definition of alternative PJ attitudes (for improved science) is an ongoing project trade.



In mid-mission orbits, Sun and Earth will be farther to the right than shown

Figure 9. Attitudes During MWR and GRAV Perijoves

GRAV likes the geometry near opposition, since small Sun-Earth-Juno angles near conjunction increase noise from the Sun's corona for X-band more so than Ka-band. MWR attitudes may also be usable in a potential extended mission, since the off-Sun angle will again be more favorable.

The apsidal rotation is shown in the bottom part of Figure 1, in which the view is from the Sun direction (there is also a geometric effect due to the rotation of the orbital plane with respect to the Sun direction). A large trim maneuver near the apojove between PJ22 and PJ23 contributes to a change in the orbit plane that avoids an eclipse (Figure 10) [10].

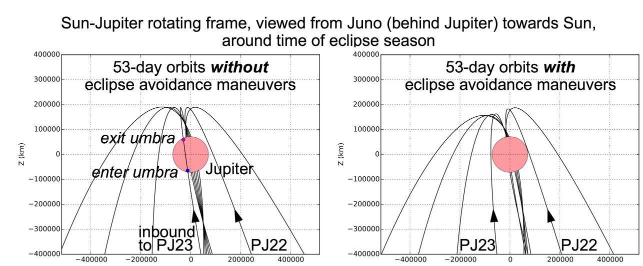


Figure 10. Eclipse Avoidance Strategy [10]

DSN Coverage — Orbital DSN coverage is required for: (a) regular verification of spacecraft and instrument health and safety, (b) downlink of spacecraft and instrument telemetry and science data, (c) uplinks (background sequences, OTMs and other spacecraft or instrument minisequences, real-time commands including contingency commands, parameter and table updates, and FSW updates), (d) two-way simultaneous Ka- and X-band Doppler for GRAV, and (e) two-way Nav X-band data for spacecraft tracking and orbit determination.

Some DSN passes use split tracks (2 or more stations, usually overlapping with telecom handovers). DSN 34- or 70-m antennas are used for all tracks, with DSS-25 required at GRAV PJ passes. All 3 DSN complexes are used, giving Nav a mix of data from northern and southern hemispheres. Figure 11 shows PJ timing with respect to DSS-25 view periods. Allowing for OWLT, it shows the timing is optimized for GRAV. With a changing DSS-25 view period (shortest around PJ23), and with longitude shifts to accomplish the required PJ pattern and spacing, GRAV usually (but not always) has enough time at the start and end: between Juno rising above 10° at DSS-25 and uplink, and between downlink of PJ+3h data and Juno setting below 15° at DSS-25.

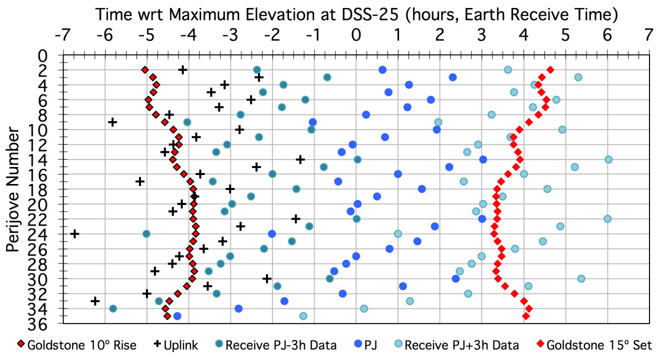


Figure 11. Goldstone DSN Timing for GRAV vs. Perijove

Data Return — Instruments manage data acquisition and return with 2 main concepts. (1) Downlink priority is cycled among the instruments to prioritize each instrument's data for an interval scaled by its allocated data volume. FGM is an exception; it is prioritized at perijove due to its baseline requirement for data in 32 orbits. (2) Each instrument uses its own data storage memory partition. If it overruns its partition, then new data are discarded. The effect is somewhat isolated from other instruments, but there is some coupling.

Since DSN tracks are planned to use a mix of 70- and 34-m antennas, the data return strategy is limited by data storage more than downlink capability. This baseline is illustrated in Figure 12, where science capability is storage-limited on all orbits except for sequences near conjunction that come close to the storage limit. Figure 16 is a data return profile for an MWR perijove sequence executed recently and the following apojove sequence (jm0071 and jm0072). A significant amount of data in an orbit are collected at perijove, then downlinked over the next few days or week or more.

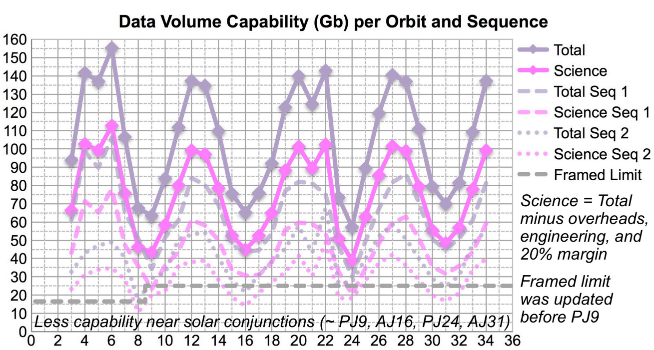


Figure 12. Science Orbits Data Return

Maneuver Strategy — The PJ+7.5h OTM accurately targets the longitude and timing of the next equator crossing, for MAG science requirements. All orbital maneuvers are expected to be done in vector mode, using both axial and lateral thrusters, so changes to the spacecraft attitude are small and the maneuvers can be viewed from the Earth. OTM uplink over a pre-PJ DSN track relies on the latest maneuver design using Doppler data acquired since the previous maneuver. OTM durations are typically 30 minutes to 2 hours. A 70-m Canberra DSN track with the MGA allow detection of carrier signal; a low telemetry rate is also usually used.

If uplink over the first available pre-PJ DSN track is missed, the OTM can be uplinked during a second opportunity. If the OTM is not executed, a backup window is available at about PJ+7d. However, whether the PJ+7d backup OTM can be used depends on the anomaly that prevented proper OTM execution. After a partially executed OTM, there is insufficient time to design and uplink a new backup OTM to finish it, so the ops team would probably skip it and wait until after the next perijove (using PJ34 to obtain MAG data at a missed perijove longitude). The OTM ΔV increases as an OTM or backup maneuver is moved away from PJ (e.g., it is ~4 times greater if delayed from PJ+7.5h to PJ+7d).

Additional maneuvers are used in 53-day orbits that were not previously required when planning 11- or 14-day orbits. An APO maneuver (near apojove) is required in most orbits to adjust range and keep PJ altitude ≤ 8000 km, and in mid-mission orbits to alter the orbit plane (inclination and node) to avoid eclipse. Backup APOs are also scheduled. Finally, a statistical trim maneuver, STM, is planned for most orbits, near PJ-14d, due to the long time between the OTM or APO and the next PJ. If prior maneuvers have exceeded delivery expectations, the STM can often be canceled. Most APOs include a deterministic component, so cannot be canceled.

Power — Power limitations expected at Jupiter's Sun range have the potential to affect science orbit plans, including in the following ways: (a) limited capability in mid- and late-mission orbits to turn off-Sun near perijove, and (b) possibly limited instrument power states (leading to time-sharing or powering off) in later orbits.

Radiation — Radiation is the main limitation to Juno's ultimate mission lifetime. However, due to the way Juno was built, nothing has been seen in Jupiter's environment so far – including radiation, magnetic field, and dust – that is expected to constrain the spacecraft and instruments from operating for the full 32 orbits (note that environmental risks vary considerably with Jovian longitude, and not all longitudes have been visited yet). As of the time of passing PJ8, all instruments are expected to last until EOM.

At science perijoves, the SRU and some of the instruments collect data (telemetry, images, and particle counts) to help monitor radiation exposure (Juno does not carry a dedicated radiation detection experiment). Some degradation of the instruments and spacecraft due to radiation damage is expected but has not yet occurred. The challenging perijove radiation environment was considered as much as possible in designing JOI and PRM, and developing plans for contingencies, e.g., safe modes or resets near PJs and OTMs.

Radiation accumulation vs. perijove is shown in Figure 13. The steep rise in radiation exposure as the line of apsides rotates late in the mission means the baseline plan includes a deorbit burn after PJ34.

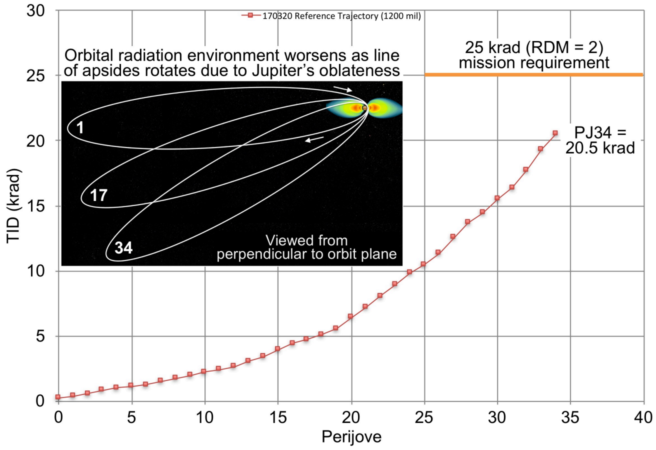


Figure 13. Radiation Accumulation vs. Perijove

Contingency Scenarios — Safe modes and C&DH resets near perijove produce a risk of losing either the PJ science pass, or the PJ+7.5h OTM, or both. The primary concern is that MAG data, required at 32 specific longitudes in the baseline mission, may be lost on 2 consecutive PJ passes, since the OTM may not be performed correctly or at all to target the next PJ longitude. Criteria for longitude tolerance provide relief relative to the need to execute a backup OTM. Mitigations for losing 2 PJ data sets include modification of the way fault protection is implemented to include MAG on in safe mode, allowing prioritized MAG data return to reduce the window of vulnerability, a backup OTM (BTM) at PJ+7d to ensure the next longitude is targeted properly, increased post-PJ DSN tracking if necessary to recover from safe mode before the BTM, use of PJ34 to make up for losing a PJ, and a science playbook (a decision tree) to ensure effective use of all options. More mitigation is available in GRAV than MWR orbits, since data are downlinked earlier.

Juno uses 70-m DSN passes soon after PJ, and frequently in other parts of the orbit, to return data in a timely way (70-m support was more critical when science orbits were planned to be 11 or 14 days long). Perijove data are desired as soon as possible, to learn about science and engineering performance during the PJ pass, in order to react by later PJs to any radiation or other environmental effects, and to update later science plans. Contingency planning for a missed DSN pass (due to a DSN problem or otherwise) relies partly on an ops process to identify data gaps during the post-PJ period or in other parts of the orbit and build retransmission commands, and partly on margin management (20% margin is applied to science data volume to allow for ~2 missed 70-m passes). It assumes most data collected in an orbit will be returned by the end of the same orbit (second sequence). PJ data account for ~15% or more of all data collected in an orbit.

Capture Orbits and Perijove 1

Following JOI at PJ0, Juno entered the first of two 53.5-day capture orbits, prior to a planned Period Reduction Maneuver two perijoves later (PJ2). It was originally planned as a single 107-day capture orbit, with PRM at the next perijove, but it was split due to the benefits of adding an intervening perijove (PJ1) [8]. This led to an early perijove without a main engine burn, which meant that instruments were on, unlike at JOI, adding weeks of valuable lead time to finalize science and instrument plans prior to PJ3 in the first shorter-period post-PRM orbit. It also provided another dip into the Jupiter environment before PRM, and more confidence regarding the execution of the maneuver. See Figure 14.

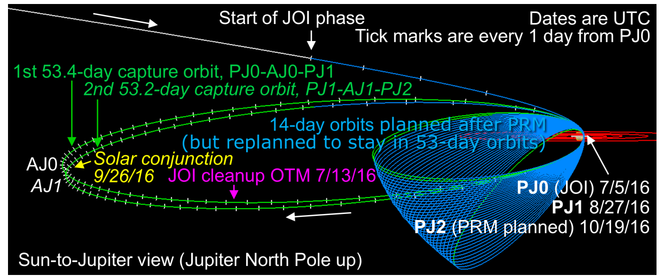


Figure 14. First 2 Orbits (Capture Orbits) and Perijove 1

To target the PJ1 longitude, a statistical OTM was planned 2 weeks after the JOI cleanup maneuver and shortly before apojove of the first capture orbit, but it was canceled due to the success of the JOI cleanup maneuver.

Due to the non-integer orbit period, PJ1 on 8/27/16 was not over the Goldstone DSN complex, so the GRAV experiment was conducted without Ka-band uplink, but otherwise the same science was conducted as in the later science orbits. It was also planned with a longitude that would contribute to the 4-8-16-32 grid for the MAG experiment. Its successful execution meant that the grid began with PJ1 instead of PJ3.

Canceled Period Reduction Maneuver and Perijove 2

An OTM was performed at PJ1+18d to target a longitude at PJ2 that had an acceptable magnetic field for performing the PRM while keeping PJ at Goldstone for maneuver coverage. Unlike JOI, which was a critical event, PRM was planned with 3 instruments on. MAG (FGM and ASC) was planned to be on, although the longitude was not one that would fit into the required grid of 32. MWR science, to collect radiometer data in a unique main engine burn attitude (spinning across multiple longitudes rather than latitudes), was also planned. These exceptions were important and were not expected to interfere with completing PRM.

During PRM pressurization, sluggish check valve actuation led to concerns about regulated main engine burn operation, so it was initially decided to delay the maneuver. After an extensive investigation, the project ultimately recommended cancellation of the PRM and remaining in 53-day orbits [10] (near-integer period, due to the need to use Goldstone at all perijoves). PRM planning included such a contingency, so this resulted in uplink of a replacement command sequence with generic science (a science sequence that can be used on any orbit), that would satisfy basic perijove science objectives (although the PJ2 longitude would still not contribute to the MAG grid).

At about PJ2-13h, the spacecraft entered safe mode due to a fault protection response to an unresponsive downlink task, in turn caused by a JIRAM high-speed recording task error. The investigation led to a spacecraft FSW patch after PJ3 (it meant further JIRAM ops were not permitted until PJ4), and ruled out possible vulnerabilities in other payload interfaces.

The spacecraft flew by PJ2 in safe mode, so X-band tracking at Goldstone was the only science (for GRAV) that was accomplished on this orbit. Safe mode recovery was done by PJ2+5d, an OTM was performed at PJ2+6d to target PJ3 (on 12/11/16, now in 53-day orbits), instruments were powered on by PJ2+9d, and a new sequence was uplinked.

Science Orbits

A Typical Orbit Timeline — Figure 15 shows the geometry and event timing for a typical orbit, in this case Orbit 7. Sequence boundaries for jm0071 and jm0072, maneuvers, and PJ and AJ times are shown. Figure 6 has some of the same information on a linear timeline for a generic orbit (xx) and includes the DSN scheduling template described below.

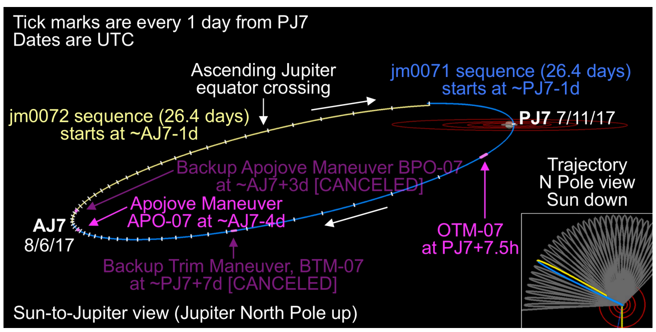


Figure 15. Example Timing and Geometry Plot – Orbit 7

The DSN template, running from PJ to just before the next PJ, specifies tracking for PJ, post-PJ downlink, maneuvers, pre-sequence boundary uplink and downlink, pre-PJ GRAV practice, and downlink roughly every other day otherwise.

DSS-25 (with Ka-band uplink) and DSS-14 (70-m) at Goldstone are required at PJ for Gravity Science and downlink of PJ data (or monitoring for non-GRAV PJs). DSS-43 (70-m) at Canberra is required to monitor the OTM. Other maneuvers including backups require 2 tracks for uplink, a 70-m for the maneuver, and a downlink track, all in ~2 days. Before the BTM at ~PJ+7d, post-PJ priority downlink uses continuous tracking through PJ+2d, then 16 hours/day to BTM-1d (providing robustness if needed to recover the spacecraft before a BTM). Pre-sequence boundary tracks (to uplink the stored sequence and related files, and the OTM prior to PJ) consist of 2 tracks before the jm0xx2 sequence, and 2 tracks each at ~PJ-3d and ~PJ-1d before the PJ sequence. A DSS-25 track at ~PJ-14d provides GRAV Ka-band practice prior to their PJ track. Finally, if not already satisfied by other requirements, at least 3 tracks per week are scheduled for additional downlink and uplink, typically during week days.

Tracking requirements include 8-hour durations usually, at least half 70-m for science downlink (aside from DSS-25), at least 2-3 weekly uplink opportunities (Denver day shift), and elevated DSN support levels at PJ mainly due to the importance and complexity of the Ka-band GRAV experiment (early orbits also elevated the support for maneuver tracks, but that requirement was relaxed with experience).

Figure 16 is output from JSOC science planning software. Colored bars near the bottom half show when instruments are on, and short vertical lines are when they change modes. Stacked colored curves at the top track stored data volumes before downlink. Decreases correspond to DSN intervals in the blue bars at the very bottom (or vertical shaded regions).

Priorities in each orbit include (not necessarily in order): (a) PJ science pass, (b) OTM and other maneuvers, (c) downlink of PJ data, (d) continuous fields and particles measurements, (e) other science and cals in non-PJ part of the orbit, (f) downlink of non-PJ data, and (g) required uplinks.

In MWR orbits, MWR uses the 6-hour perijove science pass to observe in its preferred attitude, with the spin plane passing through the center of Jupiter. JunoCam and JIRAM use the perijove opportunity to collect images and spectra. DSS-25 at Goldstone is used with the MGA or LGA to let GRAV collect X-band Doppler data. In GRAV orbits, GRAV uses the 6-hour perijove science pass to acquire two-way Ka- and X-band Doppler data and sense the internal gravity field of Jupiter in an Earth-pointed orientation. MWR, JIRAM and JunoCam also take data, since although they are not at their preferred orientation they can still see Jupiter near perijove. During all perijoves, UVS and the fields and particles instruments, JADE, JEDI, MAG, and Waves, obtain high-rate science data, focusing on the polar aurora. Waves also collects significant data in burst mode for brief intervals. In the non-perijove part of the orbit, there are calibration opportunities, plus science observations outside the near-Jupiter environment, notably at magnetic equator crossings.

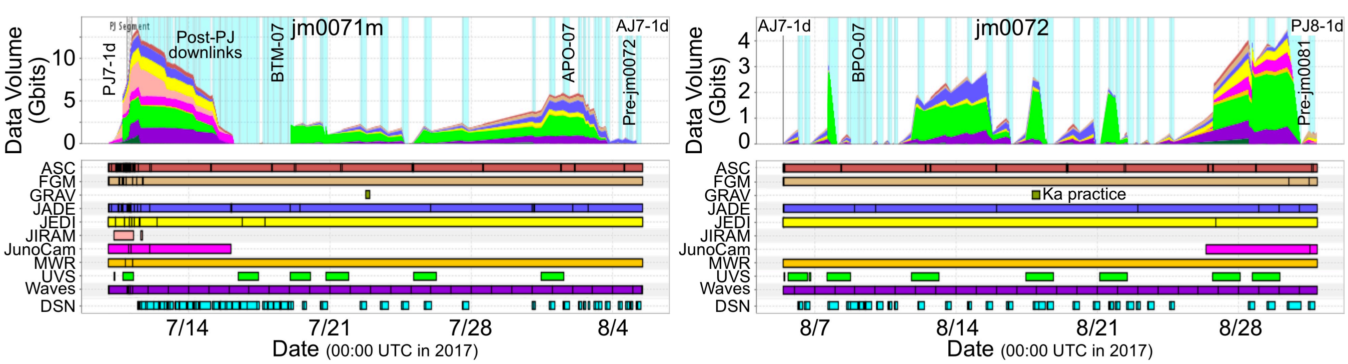


Figure 16. Example Science Activity Plans and Data Volume Profiles – Orbit 7 (parts of the DSN template are labeled)

Instrument data rates peak near perijove; decreased rates can be used in most other parts of the orbit for calibrations and non-perijove science data. Spacecraft turns are avoided between a turn to the PJ attitude at ~PJ-20h, and a pre-OTM turn at ~PJ+6h. PJ pointing stability and thermal stability is important for GRAV, MWR, and other instruments. JunoCam images Jupiter for ~5 days inbound and outbound to give context to PJ data; however, due to the changing orbital geometry relative to the Sun, this is not possible during the middle part of the mission after PJ9. UVS cycles on and off around PJ like JunoCam and JIRAM, but it also powers on and off several additional times each orbit – for table loads, an instrument decontamination activity, a stellar cal, an engineering checkout, and several 24-hour "synoptic" observations of Jupiter as it rotates. UVS has a scan mirror that lets it observe ±30° from its otherwise fixed pointing direction, giving it an effective field of view similar to the wide-angle JunoCam. Like JunoCam, UVS is constrained in observing Jupiter away from PJ in later orbits, limiting its polar auroral measurements in those orbits (mainly at the north pole). JIRAM is even more limited due to its small field of view.

Engineering rates are higher near PJ to return data important for health and safety as well as science. Spacecraft support near PJ includes telecom configurations and IMU and thruster warm-ups. SRU telemetry and images, collected while going near or through the radiation zones, supplement radiation trending data from several instruments.

Figure 17 shows stacked orbit timelines, with geometry and other information plotted on each row, plus orbit milestones (e.g., descending or ascending equator crossing, EqX-Dec or Asc), solar conjunctions, maneuvers, sequence boundaries, and Jupiter range in Rj on the horizontal axis. It gives context to repetitive orbits, while highlighting some differences.

Plans for Later in the Mission — The shifting geometry will affect science plans in future orbits. Figures 1 and 7 illustrate how the orbit normal rotates away from the Sun in the middle part of the mission, complicating efforts by remote sensing instruments to image Jupiter away from or near PJ, as well as by fields and particles instruments to sense interactions between the polar aurora and outer magnetosphere. MWR-type attitudes are desirable at those PJs, but the off-Sun pointing and resulting power concerns will not allow it unless the off-Sun angle and/or duration is minimized. Figures 1 and 17 show the inbound ascending equator crossing moving closer to PJ, so that by PJ25 it occurs within PJ-1d; by EOM it passes between Ganymede's and Europa's orbits. This will affect how magnetic equator crossings are targeted by the fields and particles instruments. Solar conjunctions (with SEP angle near 0°) near perijove at PJ9 and PJ24 (Figures 7 and 17, and table in Figure 1) will affect some of the science observatons in those orbits.

Deorbit

The Deorbit phase starts at AJ34-1h, and ends at impact into Jupiter at PJ35. To meet planetary protection requirements and ensure Juno does not contaminate Europa (or impact the other Galilean moons), a deorbit maneuver is executed near apojove. It is not as large (19 m/s, smaller than the largest

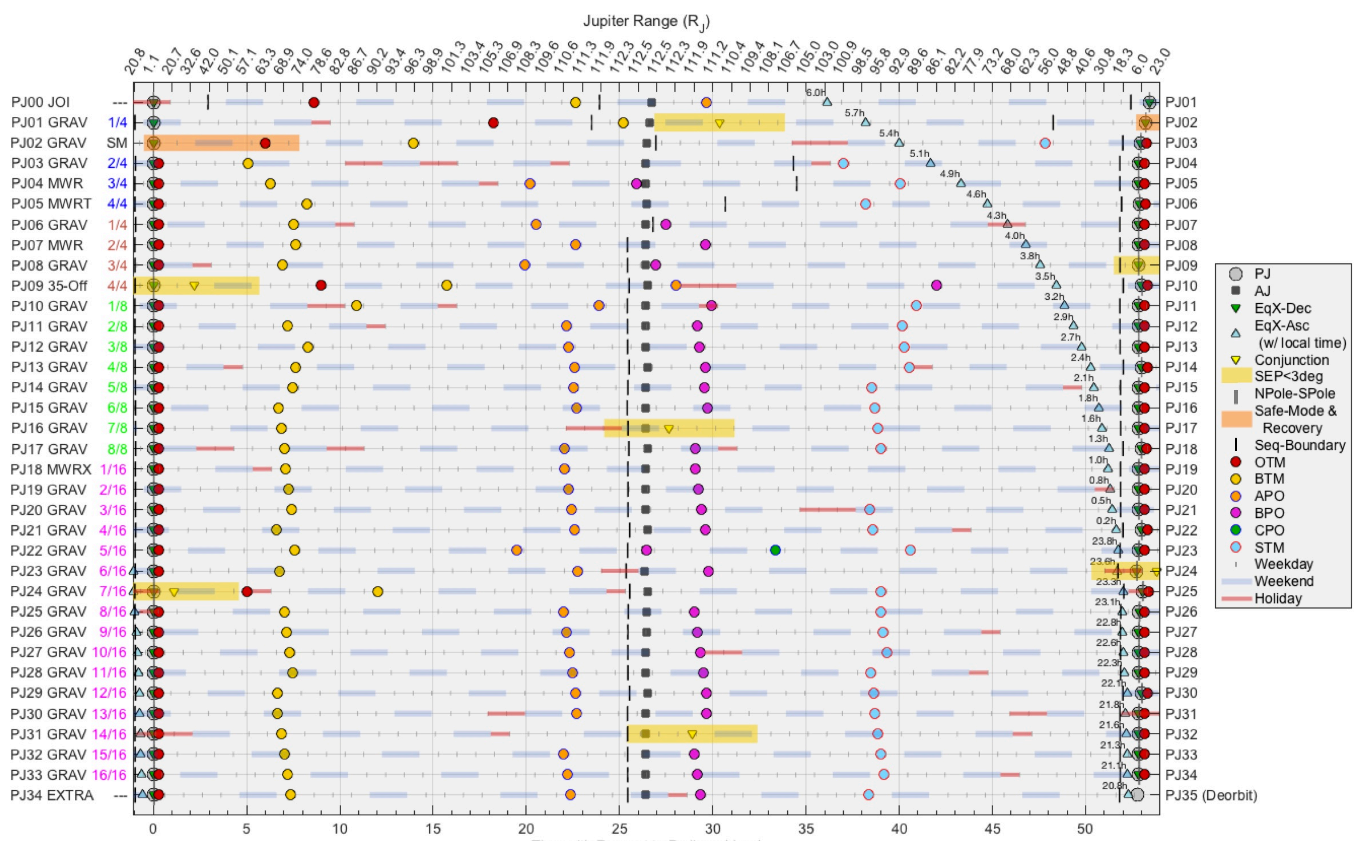


Figure 17. Stacked Linear Timelines - Geometry and Other Information for Each Orbit

APOs) as was required in shorter period orbits. Timing is not critical; contingency burns can be planned after apojove. Impact into Jupiter marks End of Mission (EOM). Continuous DSN tracking is planned from PJ34 until Impact (to return Orbit 34 science data, for Nav tracking before deorbit, to cover the burn, and to return the last data before Impact).

4. Evolution of Plan: Choices and Lessons

Juno's proposed Mission Plan purposely contained options as part of a risk reduction strategy. That plan has changed since the 2005 New Frontiers Concept Study Report (CSR) which followed a ~3-year proposal process. A draft Mission Plan document was written for the Project Mission System Review (PMSR) in 2007. A preliminary version was provided at the 2008 Preliminary Design Review (PDR), and an official initial release at the Critical Design Review (CDR) in 2009. Revisions were released during ATLO, and by the time of Rev B prior to the 2011 launch all mission phases were described with sufficient detail to outline the baseline strategy for in-flight activities, including mission-level requirements, trade studies, design features, and rationales for major decisions. Revs C and D in early cruise supported the DSMs and EFB. Since 2013, the Mission Plan has not been officially updated; however, mission planning products – timelines, trajectory data (working with Nav), graphics, and analyses (e.g., DSN downlink capability) – have been provided regularly to support JOI, PRM, and plan changes between EFB and PRM. During science ops, the Mission Plan with supporting products has served as the main source for a mission overview, geometry data, and high-level timelines.

Starting with the CSR in 2005, there were 5 main versions of the Mission Plan that can be distinguished. The others are: pre-launch (2011), post-Earth Flyby (2014), pre-JOI (2016), and the current plan (2017). They differ in 4 major categories of mission design and operations choices – related to: (a) cruise and early orbital trajectory, (b) science orbit period, (c) perijove attitudes, and (d) DSN coverage. Table 2 summarizes these choices, along with a high-level view of their effects on science data return and results, and potential lessons learned that can be applied to Juno in hindsight and possibly future missions (red highlights are used for choices that may have farther-reaching effects).

2005 New Frontiers Concept Study Report (CSR)

The 2005 New Frontiers CSR with which the project began its early design work grew out of the original proposal and contained several high-level mission concepts that ended up changing over time (Table 2). The CSR proposed a launch in 2009. The Deep Space Maneuver was one large ~1-hour burn, and Jupiter Orbit Insertion was designed to directly result in the 11-day orbital period required for science. 30 orbits built up in a grid of 15 evenly spaced longitudes 24° apart, followed by a mid-mission shift and another set of 15 longitudes that resulted in 12° final spacing. The CSR mission had 34 total perijoves (including JOI, a PJ that allowed for cleanup from JOI navigation errors, 30 science orbits, one spare PJ, and the impact PJ at EOM following a deorbit maneuver). With a 2009 launch, EOM was in 2015. Five of 30 science perijoves were planned to be flown in the MWR attitude, and the rest were GRAV. No remote sensing observations by MWR or JunoCam were planned for GRAV orbits (JIRAM was added after Juno was selected), and no GRAV observations were planned for MWR orbits. DSN tracking requirements resulted in an average ~4.5 x 8-hour tracks/week, all of which were 34-m's (70-m's were only required for main engine burns, although it was recognized early on that they may be desirable for OTMs also).

2011 Pre-Launch Mission PLan

Between the CSR (Phase A) and Launch (just prior to the start of Phase E), the Mission Plan was updated as requirements were developed, trade studies were conducted, and the spacecraft was designed, built, and prepared for launch and then flight operations. The Mission Plan document was drafted and then released at major project reviews, as well as before ATLO and launch. One of the first major changes with respect to the CSR version was the launch date; NASA requested Juno to plan for a 2011 launch, which was accommodated early in Phase B. The End of Mission timing was also updated, to October 2017.

Before PDR, the project changed its baseline interplanetary trajectory to include 2 Deep Space Maneuvers instead of 1, because splitting the DSM into 2 main engine burns avoided a costly re-qualification of the Leros 1B main engine.

Also, even prior to PMSR in 2007, a major change occurred in the way Juno was designed to transition from cruise to a regular Jupiter science orbit with a fixed period. Instead of using JOI to go directly into 11-day science orbits, a 77-day capture orbit was inserted such that JOI was moved to occur 77 days earlier than originally planned and another main engine maneuver was now required to further reduce the orbital period. This had 2 main advantages – it reduced gravity losses compared with going directly into an 11-day orbit, and it helped to minimize the ΔV required by the DSM(s) as well as total mission ΔV. More work was done to optimize the capture orbit period, so that the ATLO and pre-launch plan was for a 107-day capture orbit. The added main engine burn was the Period Reduction Maneuver, with PRM on 10/19/16, the originally planned JOI date. With the addition of PRM, the number of perijoves increased from 34 to 35.

Another major mission change that occurred early in project development was the addition of 70-m DSN support during the science orbits. The previous plan only had 34-m's for DSN coverage, but it turned out this did not meet minimum downlink data requirements in early and late orbits, when Juno was farther from the Earth (with 11-day orbits, the science mission was completed between solar conjunctions), so a single 70-m track replaced one of the 34-m's in each early and late orbit, while maintaining ~4.5 x 8-hour tracks/week.

2014 Post-Earth Flyby Mission Plan

The project deferred some orbital operations decisions until after launch. Also, with in-flight experience during cruise operations, some improvements in how to operate at Jupiter were better appreciated. An example of a deferred decision

Table 2. Evolution of Mission Plan (red font is used to highlight MP changes with respect to previous plans)

		2005 New Frontiers CSR	2011 Pre-Launch MP	2014 Post-Earth Flyby MP	2016 Pre-JOI MP	Current (Late 2017) MP
Major updates		Initial concept study report (proposal)	NF selection, Phases B-E, trade studies	Post-EFB safe modes, side swap	Decided on 14d orbits, replanned	No PRM, pre-PJ2 safe mode, replanned again
MP changes	**Cruise and early orbital trajectory**	Jun 2009 launch	Aug 2011 launch			
		1 DSM	2 DSMs			
		JOI directly to 11d orbits	JOI to 107d capture orbit + PRM		JOI to 53.5d capture orbits + PJ1 + PRM	JOI to 53.5d capture orbits + PJ1 + PJ2
	Science orbit period	11 days			14 days	53 days, & avoiding eclipse
		15-15 longitude grid			4-8-16-32 longitude grid	
		34 PJs (JOI, cleanup, 30 science, spare, impact)	35 PJs (previous + PRM)		38 PJs (previous + PJ1 + 32 science vs. 30)	36 PJs (previous - no cleanup - PJ1 now counts in grid)
		Aug 2015 EOM	Oct 2017 EOM		Feb 2018 EOM	Jul 2021 EOM
	PJ attitudes	5 MWR + all the rest GRAV		4 MWR + 1 MWR tilt	4 MWR + 3 MWR tilt	2 MWR + 2 MWR tilt + 1 MWR cross-track + TBD
		GRAV off in MWR orbits, & MWR/JunoCam off in GRAV orbits		GRAV on in MWR orbits, & MWR/JIRAM/JunoCam on in GRAV orbits		
	DSN	~4.5 x 8h tracks/week			~11 x 8h tracks/week (with 4d post-PJ continuous)	~7 x 8h tracks/week (with 2d post-PJ continuous + 5d of 16h/day until BTM)
		All 34-m	All 34-m + 1 x 70-m/orbit (early & late orbits only)	All 70-m, except DSS-25 for PJ		Mix of 70-m & 34-m, with ~3 x 70-m/week
Science implications			Capture orbit left more ΔV for science 70-m enabled meeting data return requirements	Tilt improved MWR science All 70-m ⇒ science data return limited by storage vs. downlink	Split capture orbit ⇒ early PJ1 science, & pre-PRM dip into environment 14d orbits ⇒ reduced ops risk (more ops time margin, & regular ops cadence) 4-8-16-32 longitude buildup more robust for MAG 2 additional science orbits MWR tilt ⇒ improved PJ7 Great Red Spot overflight (later updated to MWR) More DSN ⇒ improved protection for PJ science data	PJ1 now counts in grid No PRM ⇒ no cleanup at PJ3 (PJ3 now counts in grid) Potential Earth occultation (radio science) opportunity Fewer PJs ⇒ slightly less radiation Later EOM ⇒ useful orbit geometries and longer temporal baselines Attitudes potentially enable more GRS overflight(s), & other science improvements DSN ⇒ PJ science data still protected, but plays better with the user community
Specific science effects				At PJ5 (with tilt attitude), MWR obtained atmospheric emission angle dependence without aliasing in the longitudinal structure (considered crucial for understanding the water abundance)	PJ1 science & early reassurance about environment As of PJ8, 7 (of first 8) evenly spaced longitudes for MAG 2 more science orbits (32 vs. 30) potentially helps MAG Virtually all data have been returned from the PJs so far	PJ3 ⇒ earlier 4-longitude grid for MAG PJ7 GRS overflight Will explore midnight & dusk magnetosphere & boundary Improvements due to new PJ attitudes Improved GRAV & MWR data with new late-mission geometry & EOM (it may also help MAG, F&P, & others)
Potential mission planning lessons				Consider alternative science attitudes Use 70-m's to protect PJ data and ensure science data return, while playing well with the DSN; also, manage data return (so it becomes storage-limited)	Early science & dip into environment helps later science Protect ops team to minimize risk Clever orbital tour helps science (MAG in this case) Use DSN to safeguard PJ data Add more PJ risk mitigation	Complexity of magnetic field makes it more important to get all 32 PJs Longer orbits can simplify ops Minimize main engine use Require targeting Great Red Spot (vs. listing as a goal) Science benefits from a longer mission (including longer temporal baselines)

was the idea of modifying the attitude of one or more MWR perijoves to MWR tilt. This is because MWR wanted to experiment with the ground tracks of their radiometer fields of view, acquired throughout each spacecraft spin and taken at varying emission angles, so they would line up with one another on a rotating Jupiter. This means tilting the spin plane ~14° with respect to the orbit plane (Figure 9). The project decided in early 2014 to change 1 of 5 MWR perijoves to be MWR tilt, while assigning a later PJ as a backup tilt orbit.

The project confirmed during cruise that it was possible to operate the payload system with all instruments on at once. Early plans had called for no Gravity Science in MWR orbits, i.e., no X- and Ka-band operations of the telecom subsystem due to expected power limitations. The project did in-flight tests with MWR using X-band over the MGA (vs. HGA due to the off-Earth orientation), and more recently the forward LGA, that demonstrated there was no interference to MWR, and adequate link margin could be obtained for GRAV (an additional benefit is remaining in contact via carrier during PJs). Similarly, it was recognized that MWR as well as JunoCam and JIRAM could remain on at GRAV perijoves, although they would not use their preferred attitudes, with the spin plane through the center of Jupiter. This change benefited from a test of MWR and Ka-band simultaneous ops during early cruise, and both changes benefited from cruise instrument compatibility tests. Both updates occurred in mid-2014, and were made with the caveat that sufficient power has to be available during any given PJ period.

After launch and before the DSMs in 2012, Juno updated its orbital data return strategy to include 70-m's for all tracks except PJ where DSS-25 was required for Gravity Science. It was changed to allow the data return strategy to be limited by data storage instead of downlink capability, thereby maximizing science return and simplifying operations. This data return plan for 11-day orbits resulted in a science data return capability with no margin that was very close to the onboard storage limit, which was ~17 Gbits at the time (more discussion is provided in [6]).

2016 Pre-Jupiter Orbit Insertion Mission Plan

Following the safe modes shortly after Earth Flyby, and the side swap in early 2014, several changes to Juno's early orbital trajectory and science orbits were implemented in the interest of reducing operations risk, including adding margin to the 11-day orbital timeline, increasing the robustness of the high-priority MAG investigation, and providing an early way to sample Jupiter's environment with the science instruments. These updates dominate the changes to the Mission Plan between the 2014 post-EFB and 2016 pre-JOI versions (some of them were previewed in [6]).

In late 2014, as part of a trade study to enable a first look at Jupiter's environment before the orbital phase, and to reduce risks related to safe modes and other adverse effects of the environment, the project decided to split the single 107-day capture orbit into two 53.5-day capture orbits, with an intervening perijove. Splitting the capture orbit into two smaller orbits had the significant advantage of an early perijove with science instruments on. Two 53.5-day orbits resulted in a larger but acceptable JOI maneuver, and kept PRM at the same time, although it meant the new PJ1 in the split capture orbit would no longer be over Goldstone. This early science was used to satisfy 1 of the 32 required longitudes for the MAG investigation, which effectively added another spare perijove near the end of the mission.

Also, as part of the project's larger investigation into more robust orbital ops, science orbits with longer periods were investigated [6,8]. 14-day orbits resulted when trajectory designers realized that simultaneously satisfying Juno's geometry constraints (mainly buildup of an evenly spaced MAG longitude grid, and maintaining perijove over Goldstone for GRAV) can be done with new options that have periods not much longer than 11 days. Instead of achieving a grid with 24° spacing after 15 orbits and 12° after 30 like the 11-day orbits, the 14-day option takes 32 orbits, and rather than 2 it builds up 4 evenly spaced grids along the way – 4 longitudes with 90° spacing, 8 with 45° spacing, 16 with 22.5° spacing, then finally 32 with 11.25° spacing [6,8]. Also, in place of 1 mid-mission longitude shift, it uses 7 "mid-mission" shifts. The build-up is more robust for MAG since it provides multiple complete grids early, although at coarser resolution, which may partially satisfy science objectives in the event of serious mid-mission failures. The change to 14-day orbits and the 4-8-16-32 longitude grid (Figure 8) was approved in mid-2015. Corollaries to this change included 38 total perijoves rather than 35 (with PJ1 and 2 additional MAG-grid PJs), and EOM in February 2018.

With the new trajectory, it was recognized that there was an opportunity on one perijove to nearly fly over the Great Red Spot at ~20° S latitude soon after closest approach. The best viewing for MWR and other remote sensing instruments that would benefit from this is achieved with MWR or MWR tilt attitudes. By early 2016, the project adopted a baseline with 3 MWR tilt in addition to 4 regular MWR attitudes.

In 14-day orbits, as an additional mitigation for the possibility of safe mode or other adverse environmental effects near perijove, the project decided to add more DSN tracking, primarily in the post-PJ period, to support tactical operations and a potential backup OTM. This was implemented in late 2015, and included continuous tracking until PJ+4d, all or nearly all 70-m, and additional 70-m tracking near backup OTM opportunities at PJ+4d and PJ+6d. Otherwise, aside from adding a track for the longer orbit period, the pattern of coverage was similar to 11-day orbits. However, the average DSN coverage increased to ~11 x 8-hour tracks/week.

Current (Late 2017) Mission Plan

Since JOI, as a result of (a) the decision to cancel PRM and not utilize the main engine again, and (b) the pre-PJ2 safe mode, by early 2017 the project had implemented additional Mission Plan changes, all of which are related to another update to the science orbit period.

After a thorough investigation, the project decided not to do another main engine burn to reduce the period, which meant the period would remain similar to the capture orbit period of 53.5 days. The need to keep PJs over Goldstone means that period averages slightly less than 53 days.

There were several implications of this longer orbit period. An important one is that in order to fit in 32 perijoves, the mission would last long enough for the orbit petals to rotate into the midnight part of the orbit and past the anti-Sun line, resulting in the possibility of eclipse (Figures 1 and 7) [10]. Upon further analysis, it was recognized that for the planned trajectory, with 53-day orbits and nearly 90° inclination, an eclipse was possible at either or both of the inbound equator crossings before PJ22 and PJ23 (Figure 10). Juno's trajectory designers found a way to avoid eclipses by moving the orbit plane around the time of eclipse season. In effect, by allowing the inclination to increase to 105.5°, using apojove maneuvers, eclipses were avoided for the current trajectory. It turns out that for shorter-period orbits more eclipses were possible and there would have been no comparable way to avoid them, but for orbits with periods a little longer than 53 days, eclipses may have been avoidable without manipulating the orbit plane.

Other corollaries of a 53-day orbit and the choice to keep 32 science PJs and a 4-8-16-32 longitude grid (still doable for this orbit period) were 36 instead of 38 total PJs, and a later EOM, now in July 2021 (table in Figure 1). Two fewer PJs result from: (a) no PJ with a cleanup maneuver needs to be set aside after PJ2 (previously required due to the effect of PRM combined with little time to do a cleanup maneuver in shorter-period orbits), and (b) PJ1 successfully obtained magnetic field data at a longitude that would satisfy part of the first 4 evenly spaced longitudes in the current trajectory, so one fewer was needed later in the mission (see Figure 8).

With a new trajectory and longer mission, the science team recognized advantages as well as a somewhat more complicated science planning and operations strategy required due to the longer orbit and Jupiter's movement around the Sun during the longer Phase E of the mission.

Two MWR tilt orientations are planned in the current trajectory, including one accomplished at PJ5 and a modified one upcoming (as of this writing) at PJ9.

Another result of the longer period orbit is that DSN coverage per orbit can be decreased on average, and 70-m's are not required during most of the orbit as they were previously. The DSN template, described above and in Figure 6, is now ~7 x 8-hour tracks/week, including 2 days of post-PJ continuous tracking and 5 days of 16 hours/day until a BTM at ~PJ+7d. There is a mix of 70-m's and 34-m's, with 70-m coverage amounting to ~3 tracks/week out of the total.

Summary

Many of the effects on science of the Mission Plan changes described above have already been mentioned, and are listed along with additional implications in Table 2.

The 14-day orbits considered prior to the PRM cancellation and the pre-PJ2 safe mode would have given 3 extra days for anomaly recovery (more margin), as well as an operations cadence more synergistic with a 7-day week (a ~50-minute shift every 2 weeks would have resulted in a fairly consistent biweekly schedule, which is an important human factors consideration with short orbits); however, the current 53-day orbits are long enough that the pressure on the ops team of ongoing perijove planning is considerably reduced.

With 53-day orbits, the midnight orbits near the time of the avoided eclipse also offer an opportunity for an Earth radio occultation, which could be very valuable for science [10]. A potential occultation is being considered prior to PJ23.

The current trajectory decreases the total mission radiation dose, due mainly to slightly more benign geometry prior to perijoves. And the significantly longer mission offers longer temporal baselines for many science investigations. Also, more Great Red Spot (GRS) overflights are possible [10].

Additional specific science effects on individual orbits are listed in Table 2 near the bottom, along with potential mission planning lessons for both Juno and future missions.

5. Preliminary Science Results

Juno has used its early orbits to return unprecedented data on aspects of Jupiter not previously explored. Science results from PJ1 and other PJs were described in May 2017 in 2 *Science* overviews [11,12] and 50 papers in a special issue of *Geophysical Research Letters* (*GRL*, introduced in [13]).

Images of the Poles and Great Red Spot

At PJ1, JunoCam and JIRAM returned the first pictures of Juno's north and south poles. Figure 18 (reproduced from [11]), shows 3-color JunoCam images taken within a minute of maximum and minimum sub-spacecraft latitudes, with resolutions as little as 50 km. Banded structures closer to the equator give way to a darker background with chaotic regions and bright ovals. Several cyclones are clustered at each pole. Jupiter's poles are very different from Saturn's. *Geophysical Research Letters* [14-15] has more PJ1 interpretation. The ability of JunoCam and JIRAM to be on at PJs in early GRAV orbits enhanced this early science return.

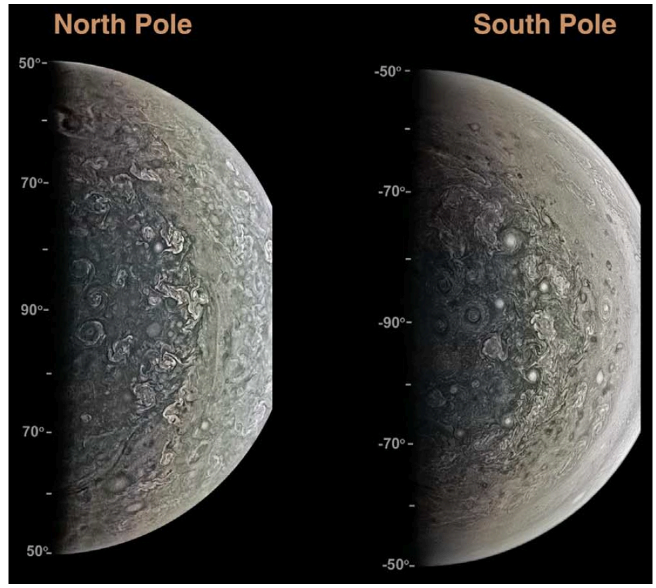


Figure 18. JunoCam PJ1 Images of Jupiter's Poles [11]

In the current mission with 53-day orbits, it was recognized early on with help from the amateur observing community that Juno would fly nearly directly over the Great Red Spot (GRS) soon after PJ7, which used an MWR attitude. Figure 19 shows 4 GRS images taken at PJ7, processed by amateurs (in time order, north up, exaggerated colors). Images are available at the JunoCam public web site [16]. The GRS is also being studied by JIRAM, MWR, MAG, and GRAV. Recognizing the value of various PJ attitudes as the mission changed led to the prospect of future GRS overflights.

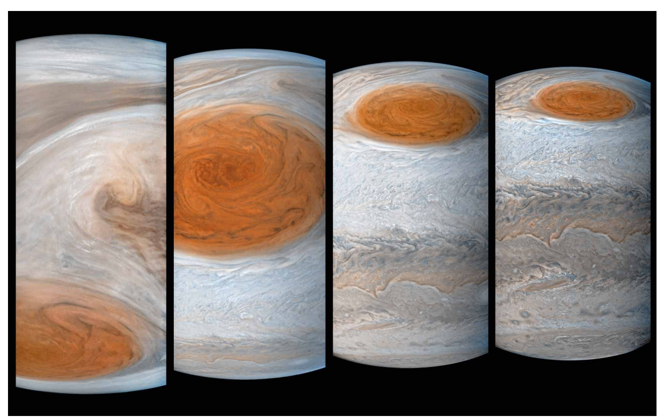


Figure 19. JunoCam PJ7 Images of Great Red Spot [16]

Deep Atmosphere

With 53-day orbits and a longer mission, at least 5 perijoves were set aside for MWR, including 2 MWR and 2 MWR tilt attitudes by PJ9. MWR was assured of having enough data to address the global water abundance and other science objectives. The PJ5 tilt attitude especially allowed MWR to obtain atmospheric emission angle dependence without aliasing in the longitudinal structure. It also gets useful data at GRAV orbits like PJ1. Significant conclusions can already be drawn from PJ1 and other early perijove data.

Figure 20, on the left, shows MWR nadir brightness temperatures in the 6 radiometer channels, with estimates of the pressure, and depth of the equivalent physical temperatures [11]. On the right side of Figure 20, variations as a function of latitude (which are similar for PJ1 and PJ3) are interpreted in terms of variations in microwave opacity, mainly due to ammonia (more so than water), and are used to infer a latitudinal cross section of ammonia mixing ratio [17]. This ammonia distribution with depth and latitude is one of the significant early findings of MWR. The variations seen in the 6 MWR channels and as a function of depth demonstrate that the weather layer extends 100s of km beneath the cloud tops, the north-south structure is asymmetric, and Jupiter is not uniform at depth. The deep structure of the GRS is also being studied.

Gravity Field

Initial Juno Gravity Science results from PJ1 and PJ2 were published in *Science* [11] and *GRL* [18-19]. With a polar orbit and such a low PJ altitude, GRAV is able to measure higher order gravity harmonics than previous missions, and dramatically increase our knowledge of Jupiter's interior. Using early data, some tentative constraints to interior models are possible. Theories are expected to be refined with more perijove data. Also, GRAV expects improvement to Doppler data in midnight orbits later in the mission due to a larger component of motion along the line of sight. A longer temporal baseline will also help to detect potential secular changes in the gravity field or pole precession rate.

Magnetic Field

Juno's magnetic field investigation has benefited from Mission Plan changes, in particular to orbit period and mission duration. A longer mission gives a better chance for observing secular changes in the magnetic field.

PJ1 reveals (Figure 21) that the magnetic field very close to Jupiter (black curve, compared to a range of model predictions in blue) is influenced by higher-order magnetic field terms, and is stronger and more spatially complex than previously modeled [11-13,20]. Early results argue for needing a full grid of 32 PJs, to investigate high-order harmonics and adequately characterize the near-surface magnetic field.

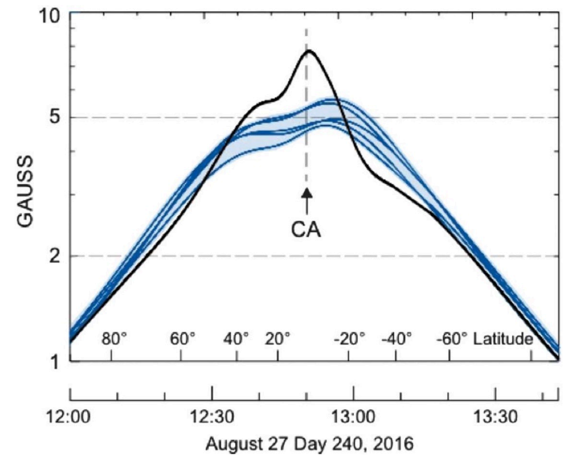


Figure 21. MAG PJ1 Magnetic Field Near Perijove [11]

Polar and Outer Magnetosphere

The polar magnetosphere is a primary objective for Juno, but it also uses its elliptical orbit to explore the outer part of Jupiter's enormous magnetosphere, especially in the current 53-day orbits. Before JOI and in early orbits, the bow shock and magnetopause were prime targets [12], and in later orbits the rotation of orbital petals will permit Juno to explore the midnight part of the outer magnetosphere, and its interaction with the polar magnetosphere and aurora. Multiple perijoves so far have allowed JADE, JEDI, MAG, Waves, and UVS to sense the magnetospheric environment before, during, and after polar auroral oval crossings.

Auroras

Juno's polar orbit lets UVS and JIRAM take unprecedented observations of the aurora at both poles, supplementing oblique views available from Hubble Space Telescope (HST) and other Earth-based platforms. Figure 22 has examples of UV and IR aurora from during PJ1 showing constantly varying structures and revealing composition [12]. Combined with data from other instruments, and comparing with what is known about the Earth, Juno is finding similarities as well as strong differences between Jupiter's and Earth's auroras [21]. Jovian aurora are also being correlated with radio emissions using Waves and Earth-based data [13].

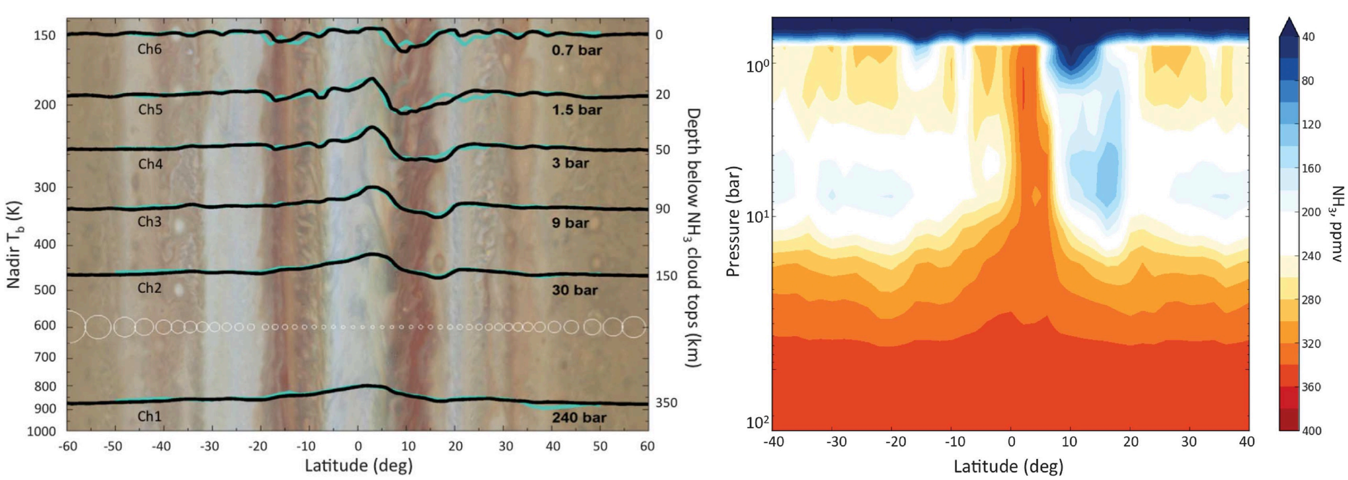


Figure 20. MWR PJ1 and PJ3 Brightness Temperatures and Ammonia Distribution [11,17]

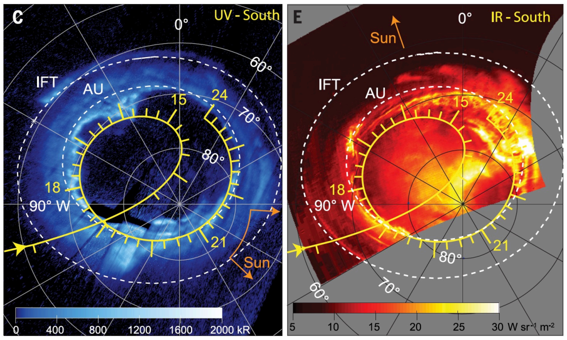


Figure 22. UVS and JIRAM PJ1 Auroral Images [12]

Radiation Environment

With an imager on one of its Stellar Reference Units (SRUs, used mainly for attitude knowledge and control), and using data from instrument sensors, Juno's radiation monitoring investigation has been able to chart inferred fluxes of both electrons and higher-energy particles in the few hours before and after each perijove. It has also sampled radiation at inner edges of the high-latitude lobes of the synchrotron emission region and in more distant environments [22].

6. SUMMARY

Brief Conclusions

Some of the science benefits of Juno's current Mission Plan, and of its evolution from earlier plans (Table 2), include:

- Early JOI and capture orbits changes led to ΔV savings that may be valuable for science in later orbits, to make up for a lost PJ or to change PJ attitudes.
- Two capture orbits led to valuable early PJ1 science, including, most importantly, providing an early up-close look into the Jupiter environment.
- Longer-period orbits reduced some ops risk, while increasing complexity in other areas. The added science – e.g., with midnight orbits, longer temporal baselines, and a potentially useful radio occultation opportunity – come with implementation challenges but constitute an overall benefit to Juno's science.
- A 4-8-16-32 longitude grid is more robust for MAG.
- New attitudes in later orbits also may lead to more GRS overflights or other science improvements.
- Larger orbits (as well as fewer PJs due to not requiring a PRM cleanup), mean less radiation.
- A mix of 70-m DSN antennas protected valuable PJ science data as well as the spacecraft (by enabling faster anomaly characterization and recovery), and enabled more science return.

Mission Planning Lessons for Future Missions

Potential lessons learned (Table 2) to help science that may be applicable to Juno in hindsight, and possibly to some future missions, include the following (from a mission planner perspective, not official project lessons – for more see [23]):

- Consider the option of using different attitudes and develop this capability during development.
- DSN strategy should ensure return of the most important data. E.g., use 70-m stations while playing well with the DSN, and manage data return so it becomes storage-limited instead of downlink-limited.
- Add more risk mitigation (not just more DSN) for the most important part of the orbit, at PJ for Juno.
- With discoveries, it can become necessary to update priorities, so design and build this flexibility during development.
- Design and develop flexibility, such as MAG on in safe mode, to reduce risk to high-priority science.
- Early science return and toe-dipping into the operational environment helps later science.
- Protect the ops team to minimize risk, e.g., mitigate against short orbits in a harsh environment.
- Consider implications for science if a post-insertion period reduction maneuver is not done. For example, Juno may have decided to capture into a 56-day orbit because that is more compatible with two 28-day sequences – or to split 107 days into 3 pieces so the orbit would not evolve around the sun as far, into eclipse season. I.e., play "what if" to investigate consequences of not executing big maneuvers. Minimize main engine use, with its inherent risk.
- Clever orbital tours, e.g., 4-8-16-32, can aid science.
- Science can benefit from larger orbits and a longer mission, including longer temporal baselines.
- Consider using requirements instead of goals, e.g., for targeting the Great Red Spot.

Table 3. Abbreviations and Acronyms

ΔV	delta velocity
AJ	apojove
APO	apojove trim maneuver
ASC	Advanced Stellar Compass
ATLO	Assembly, Test, and Launch Operations
AU	astronomical unit
BPO	backup APO (apojove trim maneuver)
BTM	backup OTM (orbit trim maneuver)
C/A	closest approach
cal	calibration
CAM	Collision Avoidance Maneuver
C&DH	Command and Data Handling
CPO	third APO-22 backup apojove trim maneuver
CSR	Concept Study Report
d	days
DSM	Deep Space Maneuver
DSN, DSS	Deep Space Network, Deep Space Station
EFB	Earth Flyby
EOM	End of Mission (Impact)
EqX	equator crossing
FGM	Fluxgate Magnetometer
F&P	fields and particles
FSW	flight software
Gbit	gigabit (1×10^9 bits)
GRAV	Gravity Science
GRL	Geophysical Research Letters
GRS	Great Red Spot
h, hrs	hours
HGA	high-gain antenna
IMU	Inertial Measurement Unit
Inc	inclination
IR	infrared
JADE	Jovian Auroral Distributions Experiment

(continued)	
JEDI	Jupiter Energetic-particle Detector Instrument
JIRAM	Jovian Infrared Auroral Mapper
JOI	Jupiter Orbit Insertion
JSOC	Juno Science Operations Center
JunoCam	Juno Camera
krad	kilorad
L	launch
Lat	latitude
LGA	low-gain antenna
LM	Lockheed Martin Space Systems Company
MAG	Magnetometer, magnetic field investigation
ME, MEF	Main Engine, Main Engine Flush
MGA	medium-gain antenna
MT, MWRT	Microwave Radiometer tilt orbit
MWR	Microwave Radiometer
MX, MWRX	Microwave Radiometer cross-track orbit
N	north, northern
Nav	navigation
OTM	orbit trim maneuver
OWLT	one-way light time
PDR	Preliminary Design Review
PJ	perijove
PJCT	perijove compatibility test
PM	periodic maintenance
PMSR	Project Mission System Review
PRM	Period Reduction Maneuver
RDM	radiation design margin
Rj, R_J	Jupiter equatorial radius (71,492 km)
RPM	revolutions per minute
S	south, southern
SEP, SPE	Sun-Earth-Probe, Sun-Probe-Earth (angles)
SM	safe mode
SRU	Stellar Reference Unit
STM	statistical trim maneuver
Sys III W Long	System III West Longitude
TBD	to be determined
TCM	trajectory correction maneuver
TID	total ionizing dose
UTC	Universal Coordinated Time
UV	ultraviolet
UVS	Ultraviolet Spectrograph
XTk	Microwave Radiometer cross-track orbit

REFERENCES

[1] Steve Matousek, "The Juno New Frontiers Mission to Jupiter: A Preliminary Design Phase Update," *International Astronautical Federation*, IAC-08-A3.6.11, 2008.

[2] Richard S. Grammier, "A Look Inside the Juno Mission to Jupiter," *IEEE Aerospace Conference*, paper 1582, December 16, 2008.

[3] Rick Nybakken, "The Juno Mission to Jupiter – A Pre-Launch Update," *IEEE Aerospace Conference*, paper 1179, January 12, 2011.

[4] Rick Nybakken, "The Juno Mission to Jupiter – Launch Campaign and Early Cruise Report," *IEEE Aerospace Conference*, 2012.

[5] Jeff Lewis, "Juno Spacecraft Operations Lessons Learned for Early Cruise Mission Phases," *IEEE Aerospace Conference*, 2014.

[6] Stuart Stephens, "The Juno Mission to Jupiter: Lessons from Cruise and Plans for Orbital Operations and Science Return," *IEEE Aerospace Conference*, 2015.

[7] Scott Bolton et al., The Juno Mission to Jupiter, science and instrument papers in *Space Science Reviews*, 2014-2017 (Magnetospheric Science Objectives, GRAV, JADE, JEDI, JIRAM, JunoCam, MAG, MWR, UVS, Waves, Radiation Monitoring, and a Juno Mission overview paper), available online at http://link.springer.com/journal/11214.

[8] Jennie R. Johannesen, Thomas A. Pavlak, and John J. Bordi, "Initial Jupiter Orbit Insertion and Period Reduction Maneuver Plans for Juno," *AAS/AIAA Astrodynamics Specialist Conference*, AAS 17-633, 2017.

[9] http://www.nasa.gov/mission_pages/juno/earthflyby.html (NASA Juno Earth Flyby web page).

[10] Thomas A. Pavlak, Jennie R. Johannesen, and John J. Bordi, "Juno Trajectory Redesign Following PRM Cancellation," *AAS/AIAA Astrodynamics Specialist Conference*, AAS 17-573, 2017.

[11] Scott J. Bolton et al., "Jupiter's interior and deep atmosphere: The initial pole-to-pole passes with the Juno spacecraft," *Science*, 356, 821-825, 2017.

[12] John E. P. Connerney et al., "Jupiter's magnetosphere and aurorae observed by the Juno spacecraft during its first polar orbits," *Science*, 356, 826-832, 2017.

[13] Scott Bolton, Steven Levin, and Fran Bagenal, "Juno's first glimpse of Jupiter's complexity," *Geophys. Res. Lett.*, 44, 7663-7667, 2017.

[14] Glenn S. Orton et al., "The first close-up images of Jupiter's polar regions: Results from the Juno mission JunoCam instrument," *Geophys. Res. Lett.*, 44, 2017.

[15] Glenn S. Orton et al., "Multiple-wavelength sensing of Jupiter during the Juno mission's first perijove passage," *Geophys. Res. Lett.*, 44, 2017.

[16] https://www.missionjuno.swri.edu/junocam/processing/ (JunoCam image processing gallery).

[17] Cheng Li et al., "The distribution of ammonia on Jupiter from a preliminary inversion of Juno microwave radiometer data," *Geophys. Res. Lett.*, 44, 2017.

[18] Yohai Kaspi et al., "The effect of differential rotation on Jupiter's low-degree even gravity moments," *Geophys. Res. Lett.*, 44, 5960-5968, 2017.

[19] Sean M. Wahl et al., "Comparing Jupiter interior structure models to Juno gravity measurements and the role of a dilute core," *Geophys. Res. Lett.*, 44, 2017.

[20] Kimberly M. Moore et al., "The analysis of initial Juno magnetometer data using a sparse magnetic field representation," *Geophys. Res. Lett.*, 44, 2017.

[21] Barry H. Mauk et al., "Discrete and broadband electron acceleration in Jupiter's powerful aurora," *Nature*, 549, 66-69, 2017.

[22] Heidi N. Becker et al., "Observations of MeV electrons in Jupiter's innermost radiation belts and polar regions by the Juno radiation monitoring investigation: Perijoves 1 and 3," *Geophys. Res. Lett.*, 44, 2017.

[23] Amy Synder Hale, "Juno's Science Planning Process: Development and Evolution Since Launch," *IEEE Aerospace Conference*, 2018 (submitted).

AUTHOR BIOGRAPHY

Stuart Stephens *received a PhD in Planetary Science from Caltech. He has been the Juno Mission Engineer since its preliminary design phase in early 2006, and has been responsible for developing and maintaining the Mission Plan. His previous work at the Jet Propulsion Laboratory (JPL) has included project experience with Galileo, Cassini, Mars Polar Lander, Dawn, and NuSTAR, as well as concept development work on Team X, in the Mission Architect Development Program, and on Discovery proposals and other NASA competed mission proposals. He has also taught high school students at the Summer Science Program in California.*

ACKNOWLEDGMENTS

I appreciate helpful reviews by several members of the current Juno team, and Figure 17 from Marty Brennan. Many people at JPL and elsewhere have contributed to the Juno Mission Plan since 2006, including past Mission Planning meeting participants, and other members of Science, Instrument, Spacecraft, Systems Engineering, Mission Design, Navigation, Mission Operations, Education and Public Outreach, and Project teams. Any errors are my responsibility.

This paper is current as of initial IEEE submission in mid-October 2017 (after perijove 8). Small changes to the Juno trajectory and perijove attitudes at the time of final submission in early January 2018 are not reflected here. (These include swapping PJ24 and PJ26 longitudes and baselining a 35° off-Sun attitude for PJ12.) It is expected that details of the Mission Plan will continue to evolve.

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.